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RESEARCH REPORT

THE EFFECTS OF OVER-TIGHTENING HIGH-STRENGTH BOLTS USED IN BOLTED CONNECTIONS IN BRIDGES

FINAL REPORT

to:

Idaho Transportation Department
Boise, Idaho

by

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16. Abstract

This report describes the research program conducted on high-strength bolts and connectors that have been over-tightened. Direct-tension indicators (DTI) may be specified for use on high-strength bolts to verify that the bolts have been sufficiently tensioned. This research was initiated at the request of the Idaho Transportation Department in order to resolve questions concerning the use of bolts installed with DTI which had been tightened to zero gap readings.

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ABSTRACT

This thesis describes the research program conducted on high-strength bolts and connectors that have been over-tightened. Direct-tension indicators (DTI) may be specified for use on high-strength bolts to verify that the bolts have been sufficiently tensioned. This research was initiated at the request of the Idaho Transportation Department in order to resolve questions concerning the use of bolts installed with DTI which had been tightened to zero gap readings.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF EQUATIONS

LIST OF PHOTOGRAPHS

LIST OF GRAPHS

LIST OF TEST MATRICES

LIST OF TABLES

INTRODUCTION

As successors to hot placed rivets, high-strength bolts have been the fastener of choice for over four decades.[1] For engineers and erectors alike, the sustained clamping force generated by high-strength bolts, especially in slip-critical connections, have made them one of the most accepted fasteners used in steel connection design. The underlying characteristic of high-strength bolts that make them so appealing is their ability to provide maximum pretension loading without excessive plastic deformation. This allows for bolts used in slip-critical connections to be tightened sufficiently to obtain the required clamping and frictional forces without undue elongation. All properly installed bolts will experience some inelastic elongation due to local yielding of the threads in the gripped part of the connection.[1] This inelastic elongation will in turn reduce the clamping force and if excessive could subsequently lessen the connection capacity during "early cycle" loading (early cycle being defined as the initial 10000 loading cycles). Thus bolt installation methods must be able to predict the pretension load accurately. Without this accuracy, the rigidity of slip-critical connections could be in jeopardy. If connections are not tightened to the required minimum pretension or are over-tightened to the point were bolt tension drops below the minimum required preload, the connection returns to a bearing type connection thus reducing fatigue life. Important financial benefits are also introduced by the ability to efficiently predict pretension loading. These benefits include lowered construction cost due to fewer call-backs to re-tighten bolts during erection. On a mechanics of material level, the proper pretension of bolts in bolted connection introduces advantageous stress patterns in connection plates.

Numerous methods have been developed to ensure that the bolts used in bolted connections are tensioned to an adequate proof load (proof load defined as 70% of max. tensile yielding load, Table 4 AISC[2]). Of these methods, the two used and evaluated in the installation of all bolts tested in this study are: 1) the Turn-of-Nut Method (Table 5 AISC[2]); for ensuring proof load by rotating the nut a specified degree of rotation beyond the finger-tight state, and 2) the more recently adopted, Direct Tension Indicator (DTI)[7]; for insuring proof load by using a washer with protrusions that compress under tension loading. Many studies have verified the reliability of both methods to achieve accurate proof loading.[1,3,4,5,6,9] However, despite the large body of documented data published on the reliability of these two methods, no data was readily available relating to the ability of these tension indicating methods to predict bolt behavior after over-tightening had occurred.

The Idaho Transportation Department (ITD) concerns centered around bolted connections in several of its bridge projects where numerous bolts had, on inspection, been classified as "over-tightened" (in this case "over-tightened" is defined as having zero DTI gaps). In general they wanted to know if a bolt designated as "over-tightened" would perform adequately.

Other questions to be addressed were: would "over-tightening" cause the bolt to exhibit severe non-elastic (plastic) elongation? If plastic elongation was induced by over-tightening would strain-hardening, necking, loss of tensile and clamping force in slip-critical connections lead to quickened ultimate failure (fracture)? Would the concentric and eccentric shear capacities of bolted connection be affected by over-tightening?

In order to determine if "over-tightened" bolts would still perform acceptably, the ITD and the University of Idaho (U of I) conducted bolt tension and shear tests on various bolt and DTI configurations, including tests conducted on bolts which were tightened according to AISC and ASTM specifications and on bolts which were "over-tightened". As a result, this thesis presents a description of these tests, the results of these tests and the recommendations to ITD based on these tests.

PREVIOUS RESEARCH

Over the last forty years, an extensive body of research has been done on the reliability of high-strength bolts (high-strength bolts being defined as having a carbon content ranging from 0.3-0.53%). Briefly stated in chronological order, the first large scale study on high-strength bolt installation was done by Bendigo and Rumpf (1959).[3] In this joint project between Lehigh University and the Pennsylvania Department of Transportation, 110 bolts were tested. The efficiency of the Turn-of-Nut method for predicting proof loading and the effects of bolt elongation and ultimate strength were investigated. The major findings from this investigation were: 1) if a bolt was installed in accordance to the turn-of-nut method, a proof load of 80% of the direct tensile ultimate load could be verified, and 2) elongation of a bolt induced by the Turn-of-Nut method was found to be less than that encountered if direct internal tension was applied (direct internal tension being defined as that produced if the bolt were tested in pure tension with no torsional component).

Munse (1967)[4] evaluated the use of hot-dipped galvanized bolts. This research demonstrated that the galling effects of galvanization could be overcome by the application of lubrication to the bolt threads during installation. Munse reported that the galling of a bolt could cause failure (failure being defined as the yielding point of the bolt) at low bolt strength (75% of direct tensile ultimate) and that this could be eliminated by the application of a lubricant (namely, beeswax).

In 1973, a group of researchers[5] looked into the reliability of DTIs (sometimes called Coronets) in friction-type joints. For both A325 and A490 bolts they found that DTIs were comparable to the Turn-of-Nut method in insuring proof load. The major advantage in using DTIs, as reported by English and American erectors, was a significant savings in installation cost. These cost savings were attributed to ease of inspection and increased speed of installation. Of secondary importance when using DTIs, the inherent strain control dependency of the Turn-of-Nut method is eliminated. Although, strain control does not reduce the accuracy of the Turn-of-Nut method, the stress control of the DTI method is easier to monitor and control.

Brockenbrough,[6] Verma & Beckmann[7] and Salih *et al.*[1] further refined the working understanding of high-strength bolts and bolted connections. Brockenbrough, focused his research on the use of weathering steel bolts (A325 and A490, Type 3, ASTM). Among his findings, Brockenbrough summarized the allowable shear stresses for different type bolted connections. His finding are given here in Table - 1. He also investigated the atmospheric-corrosion-resistance of connections wetted for prolonged periods of time. In joints exposed to long periods of wetting, Brockenbrough found that weathering steel corroded as quickly as carbon steel. As a result of these findings, Brockenbrough recommended that weather exposed steel structures using weathering steel connections should be designed to "minimize ledges, crevices and other areas that can hold water or collect debris." Brockenbrough was also one of the first to use finite-element stress analysis to evaluate joint designs.

Table 1.
Allowable Shear Stresses (ksi)*

Connection Type	A325 Bolts	A490 Bolts
Friction	17.5	22.0
Bearing - Threads in Shear Plane	21.0	28.0
Bearing - Threads not in Shear Plane	30.0	40.0

* For Standard Holes

Verma and Beckmann focused their attention on the high-strength bolts used in bridge construction. In their studies at The University of Texas, they investigated the "continued" use of substandard and mismatched bolts encountered in bridge construction. Their findings in this area were used to modify fastener manufacturing, testing and installation specifications. These modifications were intended to assure that preload tension was achieved. A summary of their Federal Highway Administration (FHWA) recommendations encompassed the topics of minimum nut strength, maximum bolt strength, thread fit tolerances, rotational-capacity testing and the need for additional bolt testing and documentation of shipping and handling requirements.

The work done by Salih *et al.* (1992) is presented in the form of an appraisal. This appraisal delineates and expands on the load-deformation properties of A325 high-strength bolts. In this appraisal, DTIs were found to ensure that the bolts meet or exceed minimum specified tension when installed properly. Also in their appraisal, and of noted interest to this research, the question of bolt over-tightening was addressed. They warned against the full closure of DTI gaps and raised the possibility of damage induced by over-tightening. These warnings of possible damages and/or loss of clamping force, slip-critical capacity, shear capacity and tensile capacity are targeted for investigation in this research.

In the Salih *et al.* (1992) appraisal only the warning to avoid complete closure of gaps in DTIs was given. They pointed to the prevention of satisfactory inspection and lack of ability to determine bolt tension if all DTI gaps are fully closed, however gave no insight into a bolt's material characteristics in the over-tightened state. In the research done for this thesis the ultimate strength of over-tightened bolts will be evaluated.

BOLTS

There are several types of bolts, other than high-strength, available for use in structural steel connection design. The type of bolt used in each design application is a function of the connection's predicted behavior, environmental exposure, connection type and overall project type (i.e. if the project is an building, bridge, etc.). The categorization of bolts available for structural steel connections is as follows:[8]

1. ASTM A307, grade A. Low carbon steel bolts.
2. ASTM A325, plain, galvanized and weathering finish. High-strength medium carbon steel bolts.
3. ASTM A490, high-strength alloy steel bolts.
4. ASTM A449 and ASTM A354 grade BD bolts. These bolts are special high-strength bolts such as interference body bolts, swedge bolts and other externally threaded fasteners and nuts.

ASTM A307 bolts only require that the manufacturer's mark appear on the bolts head. A307 bolts have a hexagonal head and are coupled with nuts that are either regular or heavy headed. The type of nut used is a function of the diameter of the bolts and is not required to have a manufacturer's mark. A307 bolts are manufactured with diameters ranging from 1/4 to 4 inches and have a specified minimum tensile strength of 60 ksi. A307 bolts are also accepted if galvanized, and thus can be used in installations requiring galvanized bolts.

Unlike A307 bolts, high-strength bolts require additional markings to be placed on the bolt as well as the nut and washer matched to them. These markings distinguish between bolt Types and Grades in addition to the required manufacturers marking (See Figure - 1).[7]

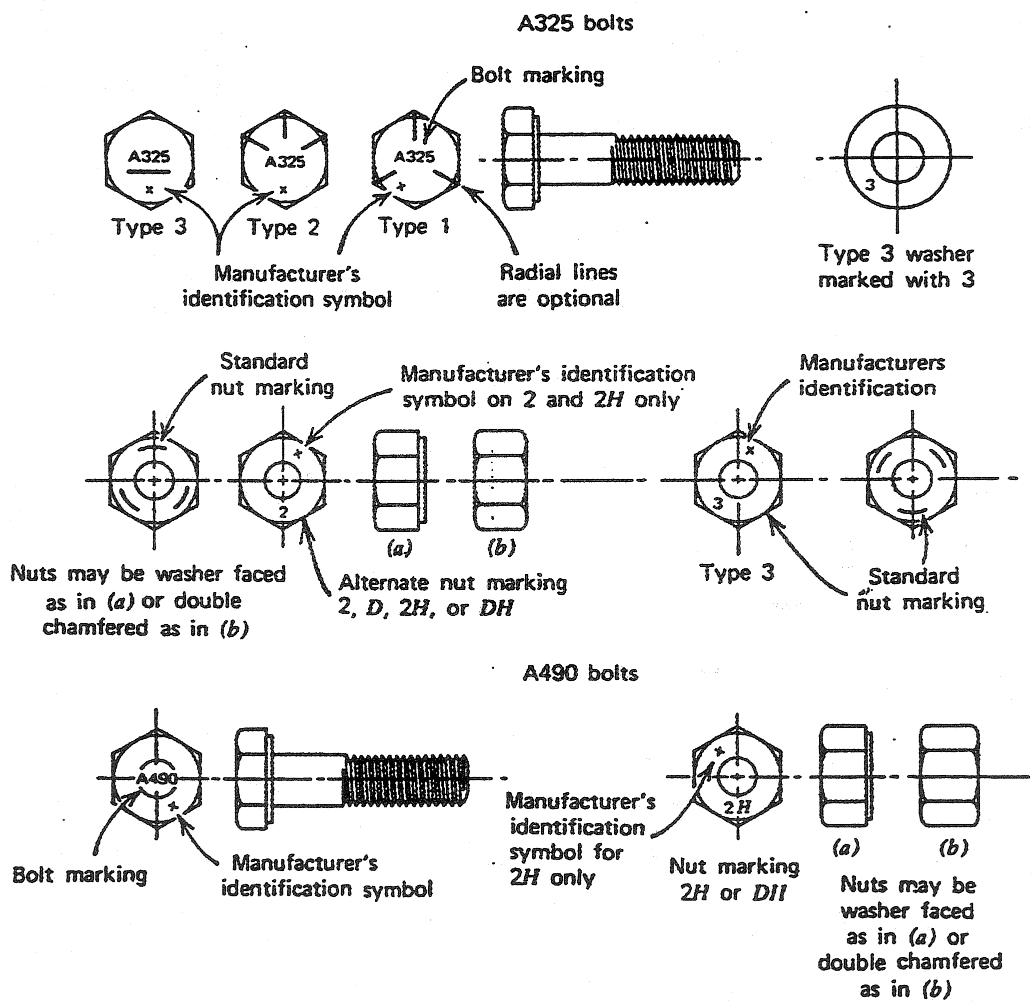


Figure 1 Bolt Markings for High-Strength Bolts

High-strength bolts are classified in two categories: A325 and A490 bolts. A325 high-strength bolts are produced from low carbon steel (max. carbon content of 0.3%). A490 bolts are produced by combining high carbon steel (max. carbon content 0.53%) and another alloy such as copper or manganese. Both the A325 and A490 bolts are heat-treated by quenching and tempering. The ultimate strength of an A490 bolt is superior to that of an A325 bolt due to its metallurgical differences and thus it is common in practice to replace A325 bolts with A490 bolts in lieu of increasing the bolt size where design capacity must be increased. One point of interest, especially to erectors, is that large diameter A490 bolts (diameters over 1 inch) are difficult to tighten adequately with pneumatic torque wrenches. Thus, if large diameter A490 bolts are specified in a connection design the method of achieving adequate tightening should also be specified.

High-strength bolts of either the A325 or A490 categories are available in three types: Type 1 is for use in elevated temperature applications; Type 2 is designed for general usage; and Type 3 is designated for corrosion resistant uses. Of these three types, the most commonly used diameters are: 3/4, 7/8 and 1 inch diameters; body lengths depend on job applications. The body lengths used in this research were either 3-1/2 or 5 inches as recommended by the ITD.

Of high-strength bolts designated A325, all must have a minimum tensile strength of 120 ksi for bolts of one inch in diameter or less and 105 ksi for bolts of diameters 1-1/8 to 1-1/2 inch. For A490 bolts, of all three types, the minimum required tensile strength is 150 ksi for diameters ranging from 1/2 to 1-1/2 in. Of these high-strength bolts only Type 1 and 2 can be galvanized. Type 3 (atmospheric corrosion-resistant) are not galvanized due to their susceptibility to stress corrosion cracking and hydrogen embrittlement.

Nuts used in conjunction with high-strength bolts are required to be manufactured in accordance to ASTM specifications A563 and must be of the heavy hex head variety. Nut grade C is specified for Type 1 and 2 bolts (uncoated).[12] Type 1 and 2 bolts that are galvanized, nut grade DH (galvanized) is specified. And for bolt Type 3 nut grade C3 is specified.[12]

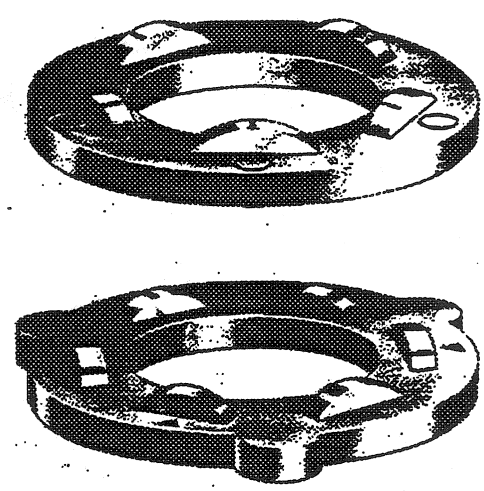
All bolts carrying the ASTM markings for A325 and A490 bolts are in turn accepted for use by the Research Council on Structural Connections (RCSC). Thus high-strength bolts that carry the A325 or A490 designation as illustrated in Figure 1 can be used interchangeably when RCSC specifications are stipulated.

Bolts and fasteners covered under the ASTM specification A449 and A354 consist of externally threaded fasteners that exhibit mechanical properties similar to A325 and A490 bolts. Bolts found in this category are interference body bolts, swedge bolts, tension-control bolts, and locking nut and bolt combinations. These bolts are designed for specific applications and will not be discussed in this report. The reader is referred to Kulak, Fisher and Struik "Design Criteria for Bolted and Riveted Joints" for further explanation of these types of fasteners and their ASTM specifications.

DIRECT TENSION INDICATORS (DTI)

"Achieving the minimum required bolt tension in a high-strength bolted friction-type joint is a primary factor, since the slip resistance of the joint is dependent on the bolt tension (Struik *et al.*)".[1] DTIs have been proven to be a good means of verifying proof load in bolted connection during and after installation. In using recommended DTI installation methods[9], the need for control over the accuracy of nut rotation of the Turn-of-Nut method is eliminated. These two reasons, coupled with the economical benefits previously mentioned, have led to the use of DTIs in many applications. However, DTIs do have one notable drawback. Using DTIs to verify proof loading is only valid as long a gap closures can be measured. Once the DTI gaps are closed to nil gaps DTIs can not verify the tension state of a bolt. Thus, DTIs can't tell if a bolt is in the initial or final state of over-tightening.

As Photograph 1 shows, direct tension indicators are hardened washers with protrusions on one face. These protrusions compress under the nut or head of the bolt as tension on the shank is induced through the tightening of the nut. This calibrated compression force ensures that proof load and slip-critical frictional force are achieved when high-strength bolts are installed via prescribed DTI methods.



Photograph 1 Direct Tension Indicators.

The two accepted methods for installing high-strength bolts using direct tension indicators are outlined in the "Instruction Manual for High Strength Bolting with Direct Tension

Indicators".[9] The main installation difference between the two methods lies in the location of the DTI's protrusions with respect to the orientation of the turned part. Method No. 1 (Figure - 2) places the DTI's protrusions away from the "turned" surface (usually the nut), whereas Method No. 2 (Figure - 3) places the DTI next to the "turned" surface. The gap acceptance criteria for the two grades of bolts are summarized in Table 2. For example, for a 7/8 inch diameter bolt, the DTI has 5 protrusions or "bumps." Proper installation of a 7/8 inch diameter A325 bolts using Method No. 1 requires 3 of the 5 gaps in the DTI protrusion ring close to less than 0.015 in measured by the refusal of the 0.015 inch feeler gage to be inserted between the DTI and bolt head (see Figure 5). For installation in accordance to Method No. 2, 3 of the 5 gaps must close to less than 0.005 in. It should be noted that these requirements are for standard building applications. For bridge construction and for epoxy coated or galvanized DTI's installed using Method No. 1, the gaps must close to less than 0.005 in. Since gaps less than 0.005 in. cannot be practically inspected, an additional increment of tightening cannot be required for Method No. 2 in these situations and should be avoided. For additional information see J & M Turner[9], (1993).

Table 2.

Bolt Size	A325 Bumps	A325 Refusals	A490 Bumps	A490 Refusals
1/2"	4	2	5	3
5/8"	4	2	5	3
3/4"	5	3	6	3
7/8"	5	3	6	3
1"	6	3	7	4
1-1/8"	6	3	7	4
1-1/4"	7	4	8	4
1-3/8"	7	4	8	4
1-1/2"	8	4	9	5

(From J & M Turner Inc. [9], 1993.)

BOLT TIGHTENING USING DTIs

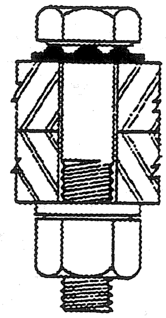
METHOD #1—(PREFERRED METHOD)—PLAIN FINISH DTIs

DTI Under the Bolt Head—Turn the Nut to Tighten

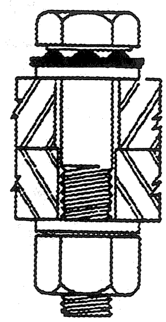
This method should be used whenever possible. Other methods are suggested but should only be used when this one cannot be.

ASSEMBLY

Put the DTI under the bolt head with the bumps facing the underside of the bolt head. Put a hardened washer under the nut.*



With a short-slotted or over sized hole under the bolt head add a hardened flat washer between the DTI and the hole.



If the bolt is an A490 and over 1" in diameter the hardened washer must be at least 5/16" thick.

TIGHTENING

Turn the nut until the gap between the bolt head and the DTI face is reduced to less than 0.015" in half or more of the entry spaces. When turning the nut, prevent the bolt head from spinning with a hand wrench. Spinning can wear down the bumps.

METHOD #1—(PREFERRED METHOD)—COATED DTIs

DTI Under the Bolt Head—Turn the Nut to Tighten

Coated DTIs should be assembled under the bolt head wherever possible. Assembly and tightening should proceed as above. For galvanized and epoxy coated DTIs the gap between the bolt head and the DTI face should be reduced to less than 0.005" in half or more of the entry spaces.

*The use of flat hardened washers per the provisions of the *RCSC Specification* varies with the bolt strength, hole size and yield strength of connected steel and tightening method. Bolt installation with DTIs should include the use of hardened washers under the turned element at all times.

For bridge applications see **INSTALLATION INSTRUCTIONS FOR BRIDGE APPLICATIONS PER FHWA**, found on the inside back cover.

Figure 2 Direct Tension Indicators Installed Using Method #1

(From J & M Turner Inc. 1993)

BOLT TIGHTENING USING DTIs (Continued)

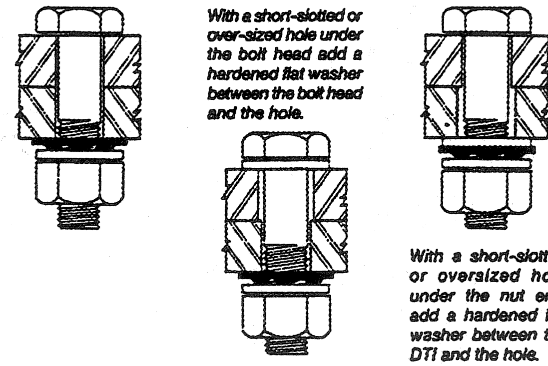
METHOD #2—(ALTERNATE METHOD) PLAIN FINISH DTIs

DTI Under the Nut—Turn the Nut to Tighten

This method should be used only when the preferred method cannot be used. It is usually limited to an installation where the DTI cannot be inspected for the proper gap if it is under the bolt head.

ASSEMBLY

Place the DTI under the nut with the bumps facing the nut. Place a hardened flat washer between the DTI and the nut.*



With a short-slotted or over-sized hole under the bolt head add a hardened flat washer between the bolt head and the hole.

With a short-slotted or oversized hole under the nut end, add a hardened flat washer between the DTI and the hole.

If the bolt is an A490 and over 1" in diameter the hardened washer must be at least 5/16" thick.

TIGHTENING

Turn the nut until the gap between the hardened washer and the DTI face is reduced to less than 0.005" in half or more of the entry spaces. When turning the nut, prevent the bolt head from spinning with a hand wrench.

METHOD #2—(ALTERNATE METHOD)—COATED DTIs

DTI Under the Nut—Turn the Nut to Tighten

This installation arrangement is not recommended, however if used the DTIs should be compressed to a gap of less than 0.005" in all of the entry spaces.

*If DTIs are installed under the turned element, hardened washers are required between the DTI and the turned element to prevent "wearing" of the "bumps." Check that the washer hole diameter conforms to ASTM F436 for sizes up to 7/8". Above 7/8", because ASTM F436 allows a washer I.D. 1/8" greater than the diameter of the bolt, which could expose a portion of the DTI "bumps," it will be necessary to procure washers made for use with DTIs. These are available from J&M Turner.

Figure 3 Direct Tension Indicators Installed using Method #2

(From J & M Turner Inc.[9] 1993.)

DTIs used in testing done for this research were of the plain, galvanized and epoxy-coated variety and were manufactured in accordance with ASTM F959. The type of DTI used in each test was matched to the type of bolt being tested. Plain bolts were matched with plain DTIs, galvanized bolts were matched with galvanized DTIs and weathering steel bolts were matched with epoxy-coated DTIs. These combinations are representative of those most commonly encountered in structural steel design practice and are used by ITD.

Additional DTI testing was conducted when notable differences were observed in the galvanized DTIs supplied. These differences consisted of two factors: first, the height and thickness of the protrusions and second, the radial distance from the center of the DTI to its protrusion. Several trends emerged in the differing DTI-protrusion configurations and were subsequently incorporated in the naming of different DTI test groups. Using the afore-mentioned trends, DTI group designations developed as follows: 1) "New Style" DTIs are identified as having the lowest and thinnest of all the protrusions investigated. "New Style" DTIs can also be visually identified as those having the smallest radial distance from centerline to protrusion; 2) The "Old Style" DTI are those with higher, thicker and farther radial spaced protrusions; 3) Of the DTI category designated "Old Style", further subdivisions were made. These secondary subdivisions are based upon the differing manufacturing marks found on supplied DTIs. These secondary classifications are: "Old Style - 325 Gap" (the 325 grade mark located in the gap between two protrusions), "Old Style - 325 Bump" (the 325 grade mark located over one protrusion) and "Old Style - B Marking" (B marking located in the gap between two protrusions). For clarification of differing DTI group designations and "Old Style" DTI manufacturers marking designations see Figure - 4. It should be noted that both the plain and epoxy coated DTIs used in testing had no differences in manufacturers' markings. Thus, only galvanized DTIs exhibited differing DTI protrusion and manufacturers' markings. It should also be noted that the designation of "Old" and "New" reflect the order in which the differing DTI protrusion configurations were encountered and do not reflect any industry standards. The classification of DTIs according to protrusion size and location, and subsequently by manufacturers' markings, was done for two reasons. First, to correlate any differences in DTI protrusion height and location and their ability to indicate accurate preload. And, second to correlate gap closure characteristics for differing manufacturers' marking categories. It is theorized that these two correlations will be used to identify the DTI-protrusion configuration that most accurately portrays the in-situ tension experienced by bolts during tightening.

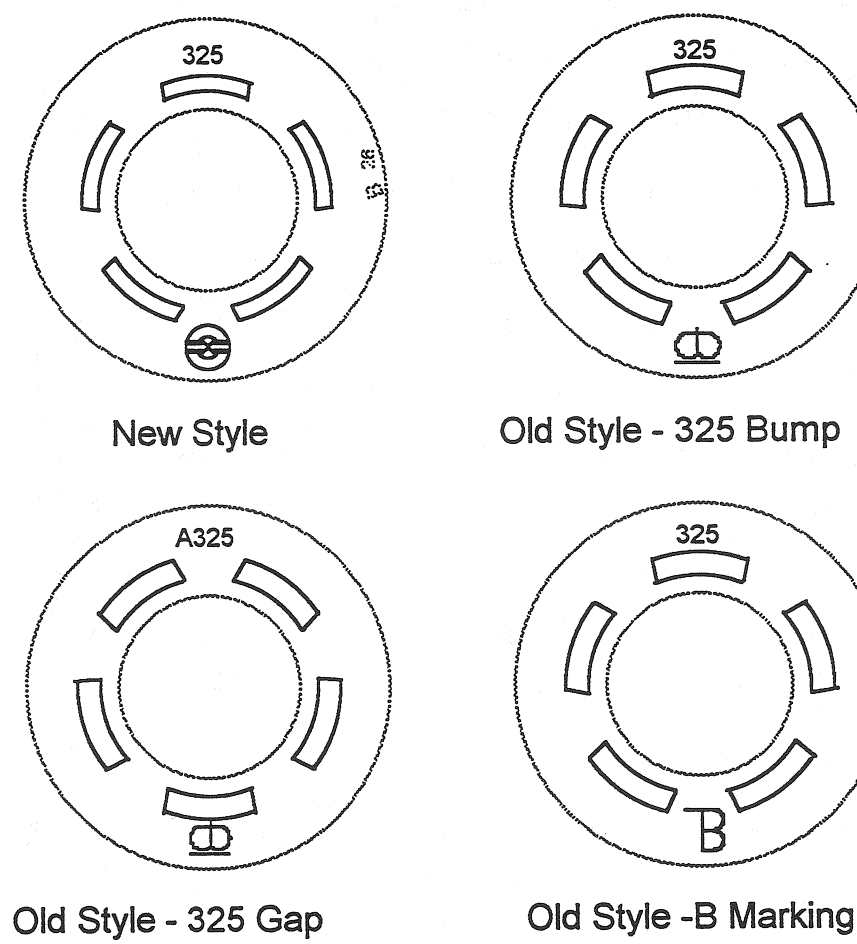


Figure 4 DTI Categories Used in the Identification of Differing Manufacturers Markings Found on Galvanized DTIs

TEST PROGRAMS

The test program implemented in this research centered on answering the basic question put forth by the ITD: What effects can be experienced by a structure designed with high-strength bolted connections in which bolts had been systematically "over-tightened"? To investigate this question, requires an accurate method of predicting when a bolt was in an "over-tightened" state. For this reason the Turn-of-Nut method was employed. Because the ITD specifies that DTIs are to be used in the installation of high-strength bolts in the construction of its bridge projects, both DTI and Turn-of-Nut methods were used in the test program. The main motivation behind the coupling of the two methods stems from the fact that the DTI method doesn't allow for the evaluation of bolt tension in the "over-tightened" state. This is due to the fact that in the "over-tightened" state DTI gaps are fully closed and no feeler gauge readings can be made. Thus the Turn-of-Nut method must be implemented to determine when a high-strength bolt is in an "over-tightened" state. Once a bolt is in the "over-tightened state, the bolts material properties can be evaluated and its reaction to the over-tightening can be analyzed.

The size and type of high-strength bolts used in this research are: Type 1 (both plain and galvanized), 7/8 inch diameter A325 of 3-1/2" and 5" body length; and Type 3 (weathering steel), 7/8 inch diameter A325 of 3-1/2" and 5" body length. These bolts were acquired from a single supplier, and all bolts supplied were produced by one of two producers, either NUCOR or St. Louis Screw (see Table 3). There were no significant differences between the bolts from the two manufacturers.

Table 3 Bolt/DTI Combinations Used in Testing			
Bolt Type	**DTI Type**	**Body Length**	**Manufacturer**
Plain	Plain	3.5"	NUCOR
" "	" "	5.0"	NUCOR or St. Louis Screw
Galvanized	Galvanized	3.5"	NUCOR
" "	" "	5.0"	NUCOR
Weathering Steel	Weathering Steel	3.5"	NUCOR
" "	" "	5.0"	NUCOR

All bolts tested were manufactured in compliance with ASTM, AASHTO and FHWA specifications and were tested "as received" with one modification, this being the application of lubricant to the threaded areas of each bolts during installation. For each bolt type, bolt-DTI combination, and DTI classification a minimum of three specimens were tested. If a significantly large variance was found in the initial three specimen tested, additional specimens were then tested.

In order to ensure uniformity in the testing procedures all but one series of bolts were installed with liberal lubrication applied to their thread area. Except for the dry bolts, before each bolt was tested, the nut matched to it was hand-threaded down and up the entire length of its threaded section prior to lubricating in an attempt to reduce data error caused by galling effects. One series of bolts was installed dry to verify the galling effect experienced by previous investigators. Galling is the binding of the thread-interface between the nut and the bolt. Galling could affect bolt behavior since the bolt shank is rotated instead elongated by turning the nut on the bolt threads. This twisting action can cause the bolt shank to shear, possibly before proof load has been reached. The results from testing these dry-installed bolts will be discussed in the analytical evaluation section of this thesis.

The test program consisted of three sections. Each section focused on a specific material property of the high-strength bolts being tested and on the response of that material property when the bolt was "over-tightened". The three test sections consisted of: 1) direct axial tension capacity; 2) concentric compressive double shear capacity; 3) eccentric tensile single shear capacity.

In the concentric compressive and eccentric tensile shear testing, a servo-controlled 500 kip Material Testing System (MTS) hydraulic ram was used. In evaluating the torqued axial tension in bolts a Skidmore-Wilhelm, Model "M", tension indicator was used. In all cases, bolt tightening was achieved through the use of a manually operated four foot, 600 ft-lb capacity torque wrench. For over-tightened bolts, this torque wrench was augmented with a 4x multiplier, thus yielding a maximum possible torque capacity of 2400 ft-lb. DTI gaps were read with a standard feeler gauge set. It should be noted that ITD used a taper tipped feeler gauge when inspecting in the field. In this testing the only difference in the two feeler gauge types was found to be in the ease with which the taper tipped gauges located the gaps between DTI protrusions. However, both sets of feeler gauges gave comparable gap readings. In Figure 5, the correct method for reading DTI gaps is illustrated using a taper tipped feeler gauge.

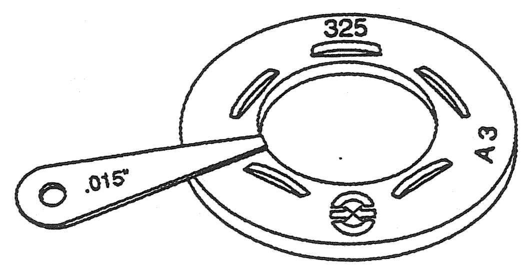


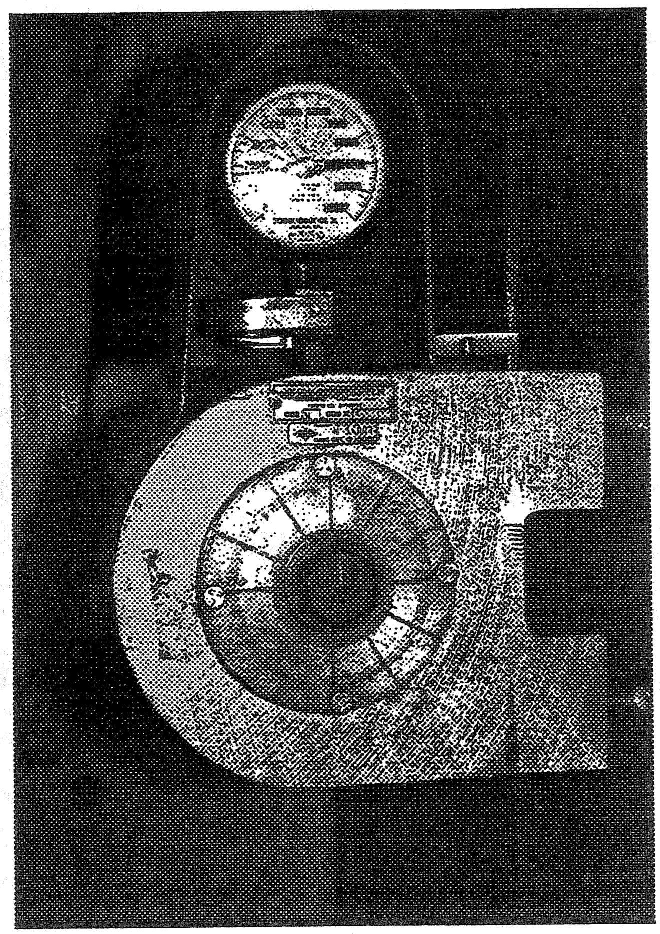
Figure 5 Proper Method for Reading DTI Gaps Using a Taper Tipped Feeler Gauge

Torqued Tensile Strength

Direct tension evaluation of bolt specimens was performed with a Skidmore-Wilhelm direct tension indicator (Photograph 2). Using this apparatus, incremental gap closure reading (DTI Method) could be correlated with nut rotation (Turn-of-Nut method) and Skidmore-Wilhelm direct tension reading. These three sets of data for each bolt tested serve to correlate the Turn-of-Nut method and the DTI gap reading method. However, once in the over-tightened state only the Turn-of-Nut can be recorded since the DTI gaps are completely closed.

See Test Matrix 1 for description of bolts tested in torqued tension.

Test Matrix 1 Torqued Tensile Strength Testing						
Bolt Identification	Type of Steel			Body Length		DTI Type Used
	Plain	Galvanized	Weathering	3.5"	5.0"	
W1			X	X		Epoxy Coated
W2			X	X		Epoxy Coated
W3			X	X		Epoxy Coated
W4			X		X	Epoxy Coated
W5			X		X	Epoxy Coated
W6			X		X	Epoxy Coated
P3	X			X		Plain*
P4	X			X		Plain*
P5	X			X		Plain*
P7	X				X	Plain*
P8	X				X	Plain*
P10	X				X	Plain*
P11	X				X	Plain
P12	X				X	Plain
P13	X				X	Plain
P14	X			X		Plain
P15	X			X		Plain
P16	X			X		Plain
G1		X		X		"Old Style"
G2		X		X		"New Style"
G3		X		X		"Old Style"
G4		X		X		"New Style"
G5		X		X		"Old Style"
G6		X		X		"New Style"
G7		X		X		"Old Style-Gap"
G8		X		X		"Old Style -Bump"
G9		X		X		"Old Style-Gap"
G10		X		X		"Old Style-Marking"
G11		X		X		"Old Style-Marking"
G12		X		X		"Old Style-Gap"
G13		X		X		"Old Style-Marking"
G14		X			X	"New Style"
G15		X			X	"New Style"
G16		X			X	"New Style"
* Indicates that Method 2 was used to install DTI.						



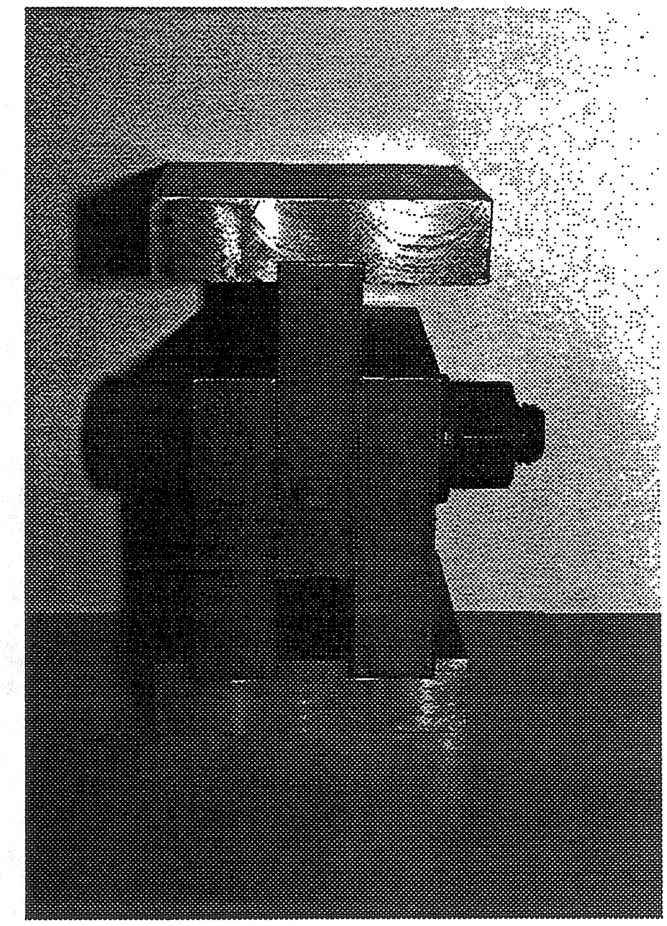
Photograph 2 - Skidmore-Wilhelm Tension Indicator, Model "M" (Rotational angle markings added by researchers to measure nut and bolt shank rotation during testing).

Concentric Compressive Double Shear

The apparatus used in testing ultimate compressive double shear is similar to that described in AISC "Specification for Structural Joints Using ASTM A325 or A490 Bolts" and that illustrated in FHWA Report No. FHWA/RD-81/148 ref (See Photograph 3). Each bolt was placed in the concentric compression testing apparatus and tightened to a "snug-tight" condition. "Snug-tight" is defined as 10 ft-lb of manually applied torque. This initial "snug-tight" condition was used as the starting point for all subsequent tightening and is done to replicate the "finger-tight" initial nut positioning used in the Turn-of-Nut method. With the nut in the "snug-tight" position, the bolt head, nut and the end of the bolt shank were marked with a permanent marker. These marks were then subsequently used as references for future sequential nut rotation readings and in establishing what, if any, rotation the bolt shank experienced during tightening. Bolts loaded to fracture in tension tests provided tension and turn-of-nut rotation data at fracture and thus defined the "over-tightened" state used in this and the succeeding test sections.

See Test Matrix 2 for description of bolts tested in concentric compressive shear.

Test Matrix 2 Concentric Compressive Double Shear								
Bolt Identification	Type of Steel			Body Length 3.5"	DTI Used	Torque Applied		
	Galvanized	Weathering	Plain			"Snug"	"Normal"	"Over"
G1	X			X	Galvanized	X		
G2	X			X	Galvanized	X		
G3	X			X	Galvanized		X	
G4	X			X	Galvanized		X	
G5	X			X	Galvanized			X
G6	X			X	Galvanized			X
G7	X			X	Galvanized			X
W1		X		X	Weathering	X		
W2		X		X	Weathering	X		
W3		X		X	Weathering		X	
W4		X		X	Weathering		X	
W5		X		X	Weathering			X
W6		X		X	Weathering			X
W7		X		X	Weathering			X
P1			X	X	Plain	X		
P2			X	X	Plain	X		
P3			X	X	Plain		X	
P4			X	X	Plain		X	
P5			X	X	Plain			X
P6			X	X	Plain			X
P7			X	X	Plain			X



Photograph 3 - Concentric compressive double shear apparatus.

A minimum of three specimens designated "snug tight" were tested in concentric compressive double shear. Additional samples were sequentially tightened using the following methodology: 1) From "snug-tight", torque was increased in 50 ft-lb increments. 2) At each 50 ft-lb increment, DTI gaps were measured and recorded. The rotation in degrees exhibited by the nut was visually measured and recorded. As a final check, the reference mark on the bolt head was visually inspected for signs of shank rotation. If shank rotation was observed it was noted on the data sheet corresponding to the bolt being tested. 3) The sequential torquing of the bolt continued until it was "normal-tight". "Normal-tight" is defined as the point when gap acceptance was met as defined by the DTI installation method being used. If the sequential tightening and reading of gap and rotation data recording continued beyond the point of "normal-tight" the bolt was designated as "over-tight." For "over tightened" bolts, the DTI gaps were closed to zero. thus the degree of over tightening is specified by nut rotation. The correlation between DTI gaps and nut rotation was verified by results of the testing described below. From these results, it was also determined that "over tightened" plain and galvanized bolts should be tightened to a nut rotation of 540 degrees (one-and-one half rotations) and "over tightened" weathering steel bolts tightened to a nut rotation of 720 degrees (two full rotations). Nine bolts were tested in concentric compressive double shear. These nine bolts consisted of three bolts each of the three tightening categories.

All of the specimens, once having reached the desired degree of tightening, were placed in the MTS actuator and displacement was applied at a constant rate such that all bolts were failed in less than 2 minutes. As displacement was being applied, a load vs. displacement plot of each bolt was graphed. This plot was subsequently digitized and the maximum ultimate concentric compressive double shear strength for each bolt tested was obtained. This data would allow for the comparison of concentric compressive double shear capacity of bolts tightened to "snug", "normal" and "over" tight conditions, respectively.

This same procedure was followed in the preparation and testing of all plain, galvanized and weathering steel bolts. For each bolt type, the specimens were tightened to the same three tightening categories.

Eccentric Single Tensile Shear

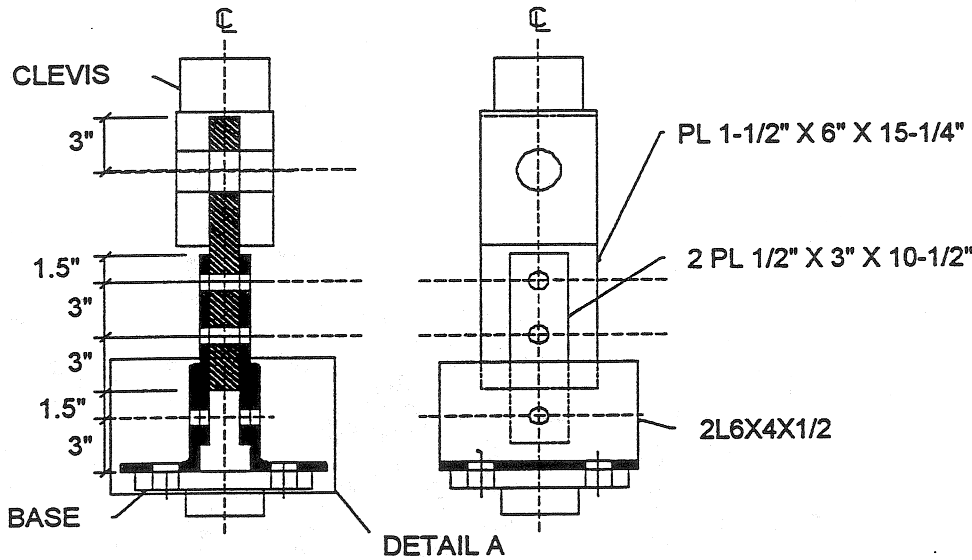
As Figure 6 and Photograph 4 show, the apparatus used in testing high-strength bolts in eccentric tensile single shear is significantly different from the concentric compressive double shear testing apparatus. Bolts tested in this apparatus, unlike the compressive apparatus, had a small eccentricity imposed on them. This eccentricity of 1/4 inch was introduced to model two-ply bridge connections.

Bolts in eccentric single tensile shear, as in the double compressive shear tests, were manually torqued. In this test, only weathering steel bolts were tightened to 0, 260, 360 and 540 degrees of rotation respectively using the same methodology described in the previous section. Due to the symmetry of the test apparatus two bolts were tested simultaneously. Thus a total of eight bolts were tested in eccentric single tensile shear.

Stroke was applied to each specimen at a rate sufficient to cause failure in under 2 minutes and data was collected via a simultaneous plot and subsequently digitized. In short, the only differences between the concentric compressive and eccentric tensile shear test lies in the apparatus used for testing, the eccentricity introduced in the tensile shear testing and in the fact that the tensile shear testing was done in single and not double shear. The procedures used in the installation and tightening of both compressive and tensile shear specimen were the same. This tensile shear data, like that of the compressive shear test, would allow bolts to be evaluated on the basis of both bolt type and tightening criteria.

See Test Matrix 3 for a description of bolts tested in eccentric tensile shear.

Test Matrix 3 Eccentric Single Tensile Shear							
Bolt Identification	Type of Steel Weathering	Body Length 5.0"	DTI Used	Torque Applied (Degrees of Rotation)			
				0	260	360	540
T1	X	X	Plain	2			
T2	X	X	Plain		2		
T3	X	X	Plain			2	
T4	X	X	Plain				2
All bolts weathering steel							



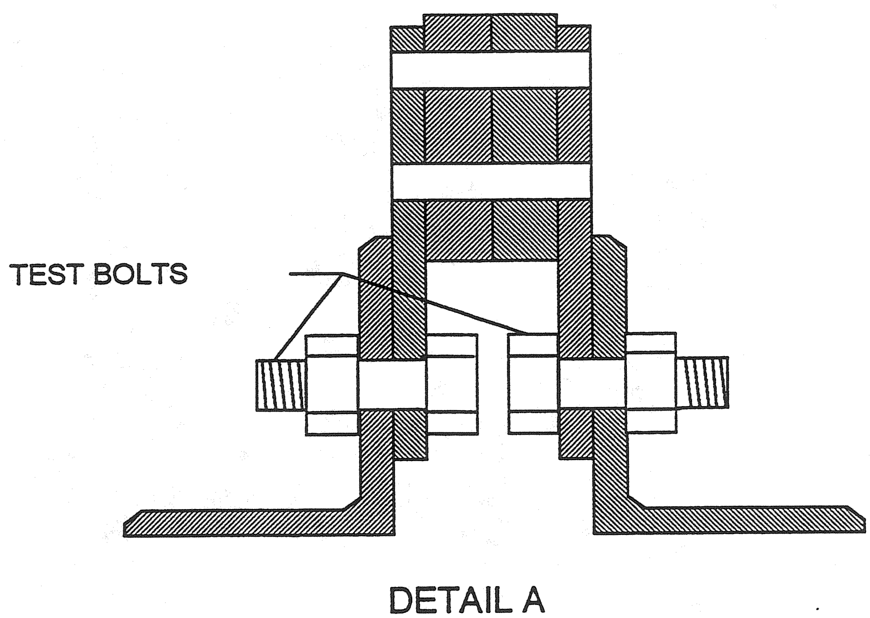
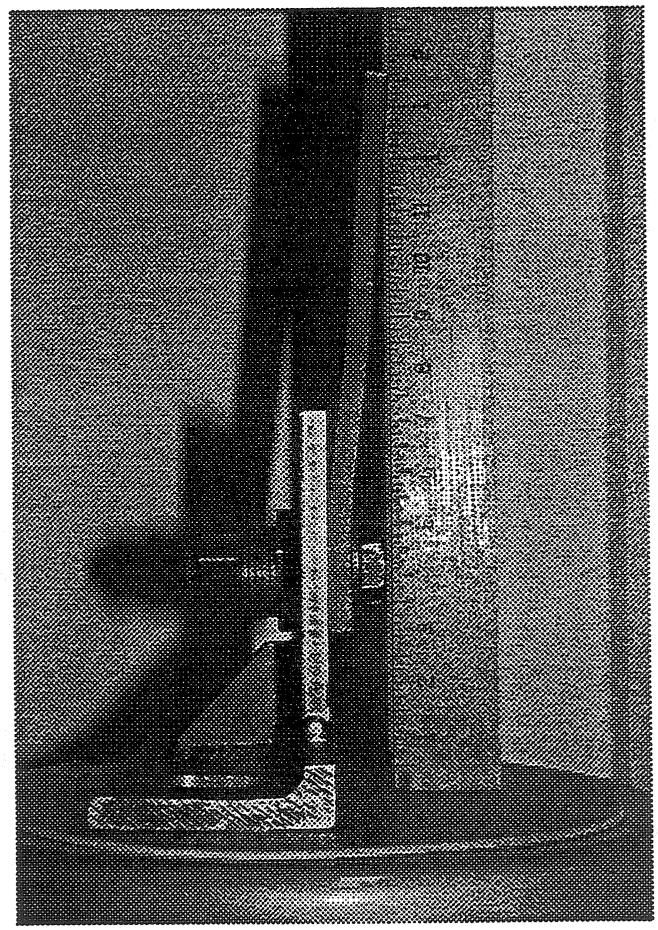


Figure 6 Eccentric Tensile Single Shear Apparatus



Photograph 4 - Eccentric tensile single shear apparatus (after testing).

ANALYTICAL EVALUATION

Torqued Tensile Strength

As a bolt is tightened, torque is applied to the nut. A portion of this initial nut torque is transmitted to the shank of the bolt through frictional forces located in the nut-bolt-thread interface. This generates combined tension-torsion stress in the bolt. To evaluate the actual torqued tensile strength of a bolt, ASTM requires that direct tension and torqued tension testing be done[7]. Thus, the ultimate tensile strength of high-strength bolts in their direct tension state can be compared to their combined tension-torsion state. As a result of comparing the direct tension and torqued tension ultimate shear capacities for numerous A325 and A490 bolts, ASTM has found up to a 15% reduction in strength of bolts in torqued tension compared to bolts in direct tension.[10, 11]

Due to the combined tension-torsion stress introduced by the friction between the nut and the gripped portion of the bolt as the nut is rotated, bolts in tension are evaluated by the performance of their threaded sections. When a bolt is subjected to axial loads, its elongation characteristics (Load vs. Elongation) determine the bolt's performance. This dependency on elongation characteristics is the reasoning behind the ASTM specifications for proof loading requirements. ASTM defines proof loading to be about equivalent to the yield strength of a bolt or loading causing 0.2% offset elongation.[12, 13] To be doubly sure that high-strength bolts meet ASTM strength requirements, both minimum tensile strength and proof loading requirements must be met. Both the DTI and Turn-of-Nut methods are accurate in estimating proof load using either criteria. Minimum tensile strength is calculated using Equation 1:

Theoretical Nominal Tension Strength.

$$R_n = F_u^b\left(0.75A_b\right) \qquad \textbf{Equation - 1}$$

R_n = Nominal resistance capacity.

F_u^b = Tensile strength of bolt material (120 ksi for A325 bolts; 150 ksi for A490 bolts)

A_b = Gross cross-sectional area across the unthreaded shank of the bolt.

0.75 = Multiplying factor to represent the threaded portion of the bolt.

For a 7/8 in. diameter A325 bolt, the theoretical tensile strength R_n = 54.1 kips. The proof load for this bolt is 70% of the theoretical strength or 39 kips (173 kN).

The test results for the direct tension loading bolt series are summarized in two forms. The first format is illustrated in Graphs 1 through 12. In these graphs, the data collected on the torqued tensile strength of the bolts is plotted as Normalized Tension Load vs. Nut Rotation. Normalized tension is defined as the ratio of the experimentally determined tension divided by the proof load, 39 kips. The second form of the data collected for this section of the research is found in Graph 13a through Graph 22b. In these graphs the data is presented as Bolt Tension vs. Average DTI Gap. In Graph 13a through Graph 22b units are given in a dual scale format consisting of both SI and US Customary units.

Graphs 1 through 12 were used to evaluate the over-tightening of high-strength bolts up to and beyond zero DTI gap using the Skidmore-Wilhelm direct tension indicator and Turn-of-Nut method in unison. These graphs illustrate the typical load vs. nut rotation relationship one would expect in the evaluation of the Turn-of-Nut method. Specifically, as the degree of rotation experienced by the nut increases the direct tension load experienced by the bolt's shank also increases. In each of these plots one can see the three distinct characteristic expected in a load vs. deflection plot of a ductile metal. The three characteristics are: 1) a fairly linear initial section; 2) a yielding point; and finally 3) a ultimate failure (rupture) point.

The transition from linear to yielding behavior typically occurs shortly after the bolt reaches proof load. This transition coincides with the closure of the DTI gaps to the specified limits, as indicated by the vertical lines on Graphs 1 through 12. The proof load and gap closure limits are reached at nut rotations of 270 to 450 degrees (three-quarters turn to one-and-one-quarter turn). The gap closure limit also indicates the *onset* of overtightening.

Rupture of the bolts occurred at nut rotations ranging from around 540 (one-and-one-half rotations) to more than 720 degrees (two full rotations) depending on the bolt type and lubrication. In order to detect the effects of over tightening, it was desired to tighten the bolts as much as possible without rupturing them. Thus the "over tightened" plain and galvanized bolts were tightened to nut rotations of 540 degrees, and the "over tightened" weathering steel bolts were tightened to rotations of 720 degrees. While preparing "over tightened" specimens for shear testing, several bolts were ruptured before achieving the rotations specified.

Graph 13a through Graph 22b show the average gap reading vs. tension load for the same bolts plotted in the previous graphs. These gap reads were made at the same time the torqued tension readings were being read from the Skidmore-Wilhelm tension indictor. Since the data for the Turn-of-Nut and DTI were recorded simultaneously for each same bolt, any error in comparing the two is felt to be minimized. Thus considering the data generated in Graphs 1 - 12 and comparing it to the data plotted Graphs 13a - 22b, a good assessment of the reaction of DTIs to over-tightening can be made. In looking at plots 1 through 12 and identifying the onset of over-tightening via the Turn-of-Nut method and transferring this information to plots 13a through 22b, a positive correlation between the Turn-of-Nut and DTI for establishing bolt behavior in the over-tightened state can be made. With this information, the method specified for installation of high-strength bolts and DTIs by the ITD can be evaluated in their over-tightened state by correlation when the onset of over-tightening occurs through the use of the Turn-of-Nut method.

As stated earlier, the general trends in both sets of data support those conclusion made in the previous paragraph, however some differences in the data must be described. The first is regarding data collected by the two DTI installation methods. In the installation of high-strength bolts via Method 2, a combined flattening and shearing of the DTIs protrusions was observed. However, the DTIs installed via Method 1 illustrated only pure compression characteristics when observed after installation. This observation suggests that Method 1 may be a more desirable method of installation if connection details and/or site conditions allow for bolt installation via this method. It should be noted that a majority of bolts tested for this research were installed using Method 1. This was done to minimize the combined shear effect on the DTI protrusions witnessed in the use of Method 2.

Shearing of the DTI protrusion in the installation of high-strength bolts via Method 2 was observed to be intensified in the use of "Old Style" DTIs. This is due to the fact that "Old Style" DTIs have higher and thicker protrusions. Thus, with more material exposed to the friction generated by installation Method 2, higher variances in DTI tension readings where seen. This trend culminated in the reading of lower tension loads when compared to comparable gap closure readings using Method 1. However, with the exception of the plain 7/8" diameter 3/5" length bolts no tension readings were below proof load at gap acceptance when installation Method 2 was used.

Of the differing galvanized DTI categories, the one designated "New Style" was found to have the smallest variation in Bolt Tension vs. DTI Gap Closure plot data. When "New Style" DTIs were used, the scatter experienced in the collection of gap closure data was reduced. This can be seen in the closeness of the 95% survival line to the mean regression line of Graphs 13a - 22b. The distance from the mean regression line to the 95% survival line is a direct product of the amount of scatter; thus the deviation of data collected for the "New

Style" DTIs is reduced as is the distance between the 95% survival line and the linear regression line.

Gap closure data for the weathering steel and plain steel bolts were also witnessed to have smaller variances in gap closure readings when compared to the "Old" categories of galvanized DTIs. This is due to the fact that the epoxy-coated and plain steel DTIs had the same geometry as the "New Style" DTIs. Thus, adding evidence that DTIs with lower and closer radially spaced protrusions better model the actual tension experienced by high-strength bolts during tightening.

Of interest is the load at which the bolts fractured - specifically the tension loss immediately prior to fracture. This is important in light of recent tension research done by other researchers on high-strength, galvanized bolts. In these studies, galvanized bolts have been witnessed to exhibit tensile strengths below proof loading between the onset of yielding and ultimate failure (rupture). This data would indicate that if high-strength, galvanized bolts are "over-tightened", a significant loss of preload could be experienced by the bolt. This data would point toward the need for additional tightening criteria to establish a maximum tightening procedures for galvanized high-strength galvanized bolts. Like the Turn-of-Nut and DTI installation methods currently being used to assure minimum preloading is established, these new installation specifications would protect against the significant loss of preload in over-tightened high-strength galvanized bolts. These new specifications would provide a maximum allowable amount of rotation from "Snug-Tight" for the Turn-of-Nut method and a rejection of galvanized bolts if all gaps are closed for DTIs.

It should be noted that for all high-strength, galvanized bolts tested in this research, the plastic range tension loss prior to ultimate failure did not drop below the proof load prior to rupture. However, during the installation and testing of the various high-strength bolts for this research, it was apparent that if bolts were manufactured with highly ductile material characteristics, it would not be unlikely that plastic state tension losses and resulting loss of clamping force could become significant and thus degrade a connection from a slip-critical to

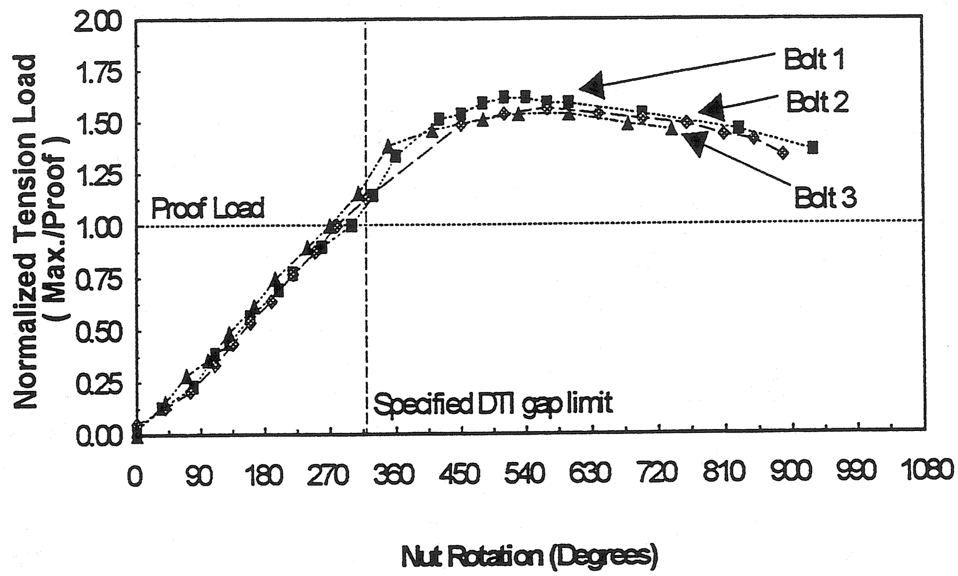
Table 4
Defining the Rupture Limit for Bolt/DTI Combinations

Bolt Type	DTI Type	Body Length	Nut Rotation at Rupture (degrees)
Plain	Plain	3.5"	>540
" "	" "	5.0"	>540
Galvanized	Galvanized	3.5"	>540 *
" "	" "	5.0"	>540 *
Weathering Steel	Weathering Steel	3.5"	>720 *
" "	" "	5.0"	>720 *

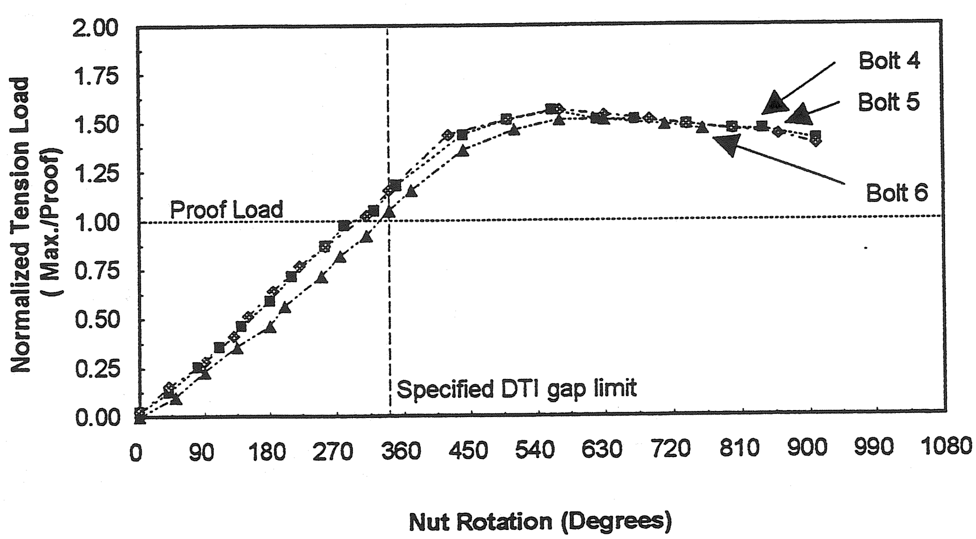
* Heavier Thread Lubrication Used.

a bearing connection thus losing all beneficial fatigue characteristics. For a summary of nut rotations at point of rupture for the bolts tested in this research see Table 4. .

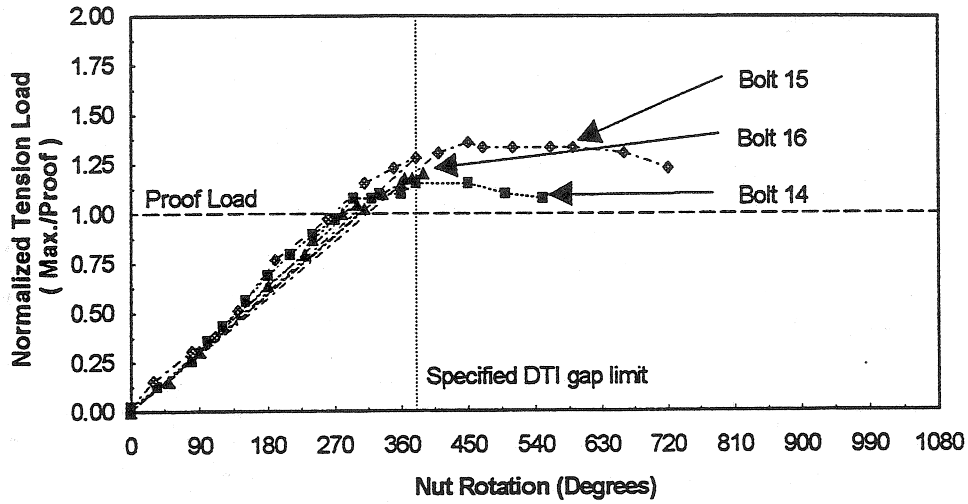
One point of interest is that the bolts plotted in Graph 5 were installed with a minimal amount of lubricant applied to them. This plot shows that a significant loss of bolt tension can be exhibited by poorly lubricated bolts. As this plot shows, in comparison to bolts installed with exhibited by poorly lubricated bolts. As this plot shows, in comparison to bolts installed with liberal lubrication, poorly lubricated bolts can show a torqued tension load reduction of up to 30%.



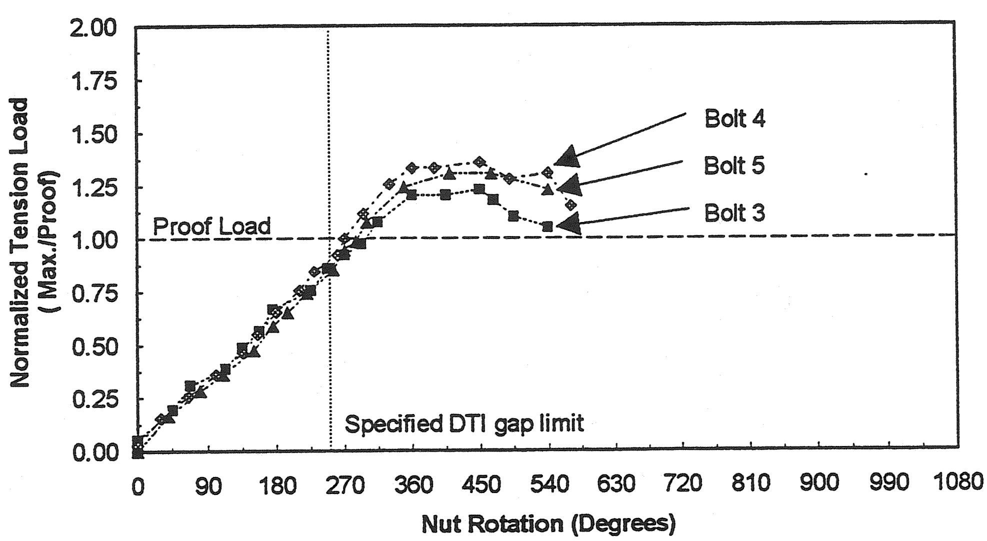
Graph 1 - Normalized Torqued Tension Vs. Nut Rotation Weathering Steel 7/8" Diameter, 3.5" Body Length A325 Bolts. Epoxy Coated DTIs, Installed using Method 1.



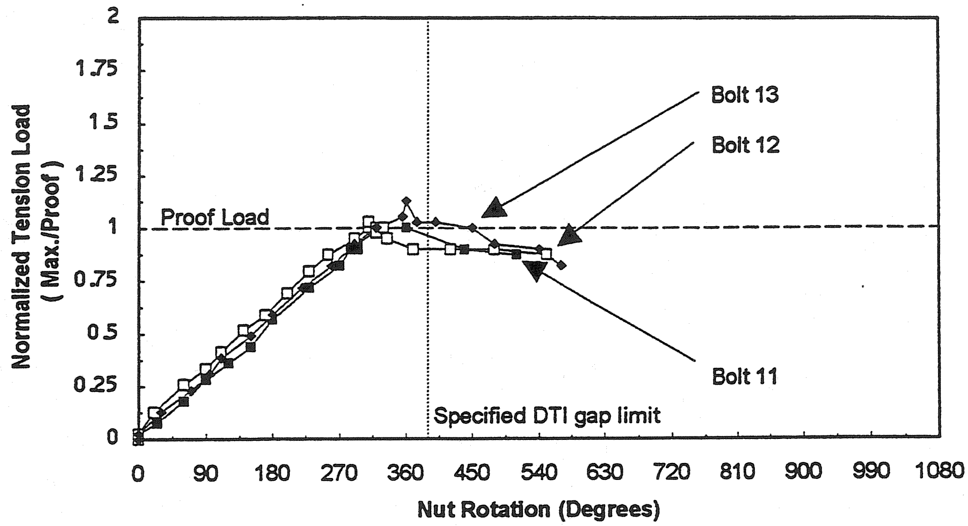
Graph 2 - Normalized Torqued Tension Vs. Nut Rotation Weathering Steel 7/8" Diameter, 5" Body Length A325 Bolts. Epoxy coated DTIs, Using Method 1.



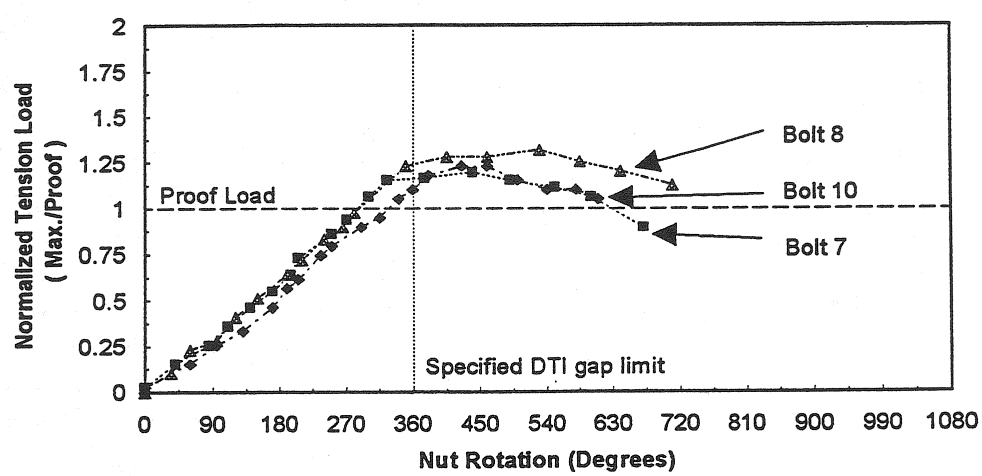
Graph 3 - Normalized Torqued Tension Vs. Nut Rotation Plain 7/8" Diameter, 3.5" Body Length A325 bolts. Plain DTIs, Installed using Method 1.



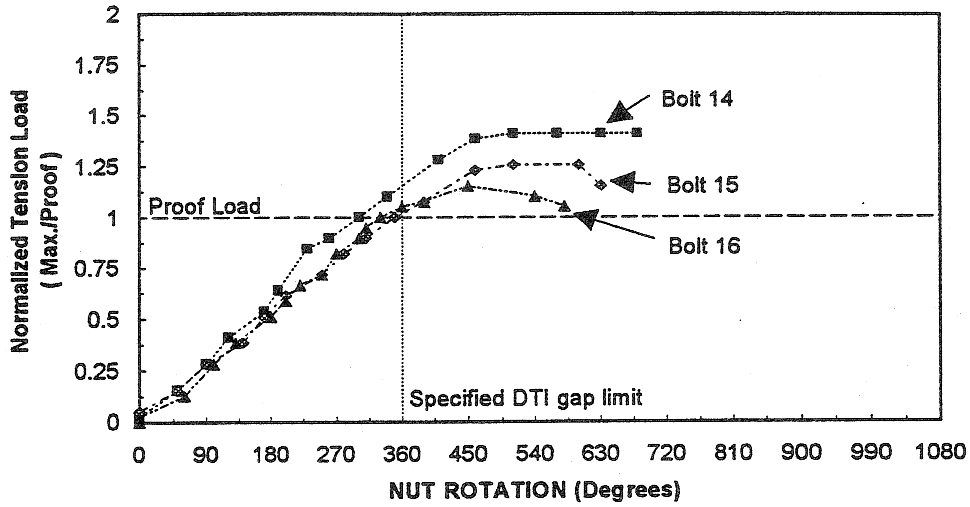
Graph 4 - Normalized Torqued Tension Vs. Nut Rotation Plain 7/8" Diameter, 3.5" Body Length A325 Bolts. Plain DTIs, Installed using Method 2.



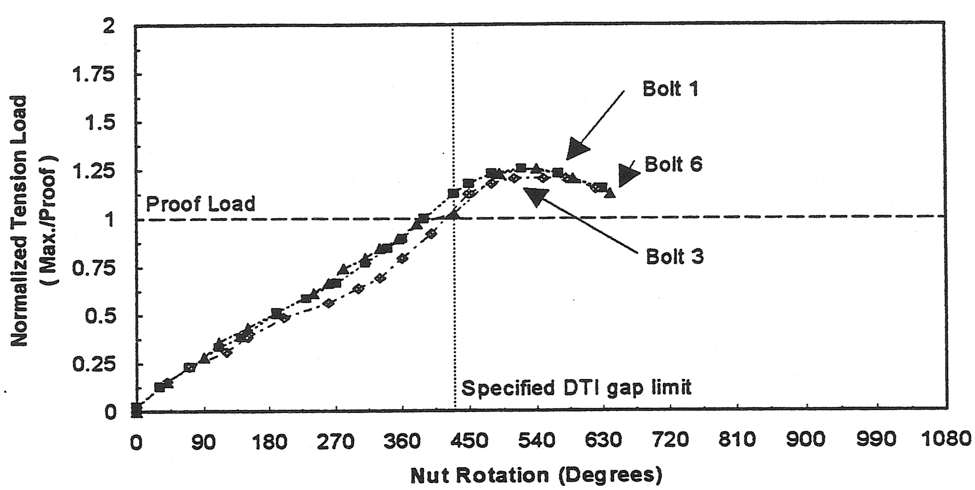
Graph 5 - Normalized Torqued Tension Vs. Nut Rotation Plain 7/8" Diameter, 5" Body Length A325 Bolts. Plain DTIs, Installed using Method 1. (Dry)



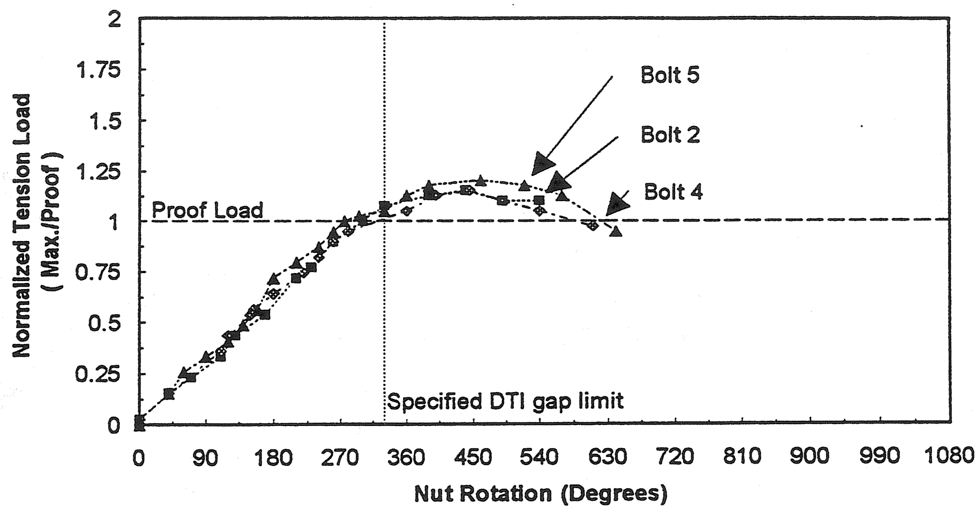
Graph 6 - Normalized Torqued Tension Vs. Nut Rotation Plain 7/8" Diameter, 5" Body Length A325 bolts. Plain DTIs, Installed using Method 2.



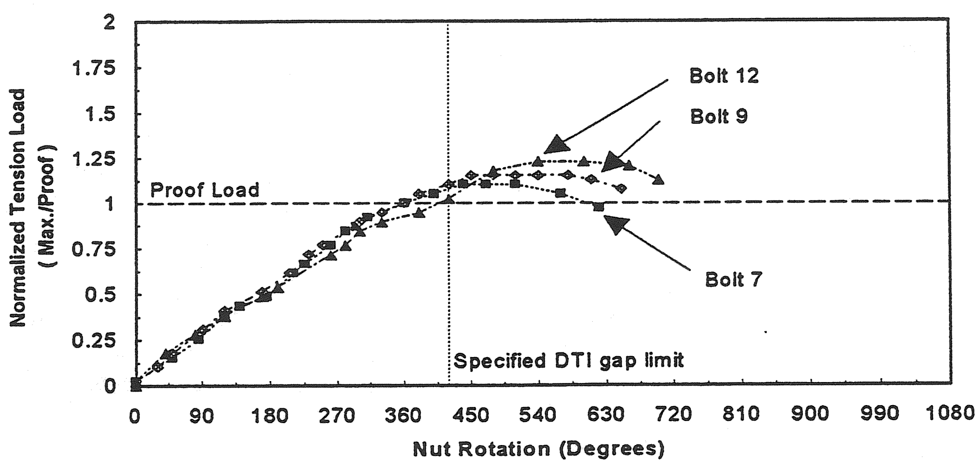
Graph 7 - Normalized Torqued Tension Vs. Nut Rotation Galvanized 7/8" Diameter, 5" Body Length A325 Bolts. Galvanize "New Style" DTIs, Installed using Method 1.



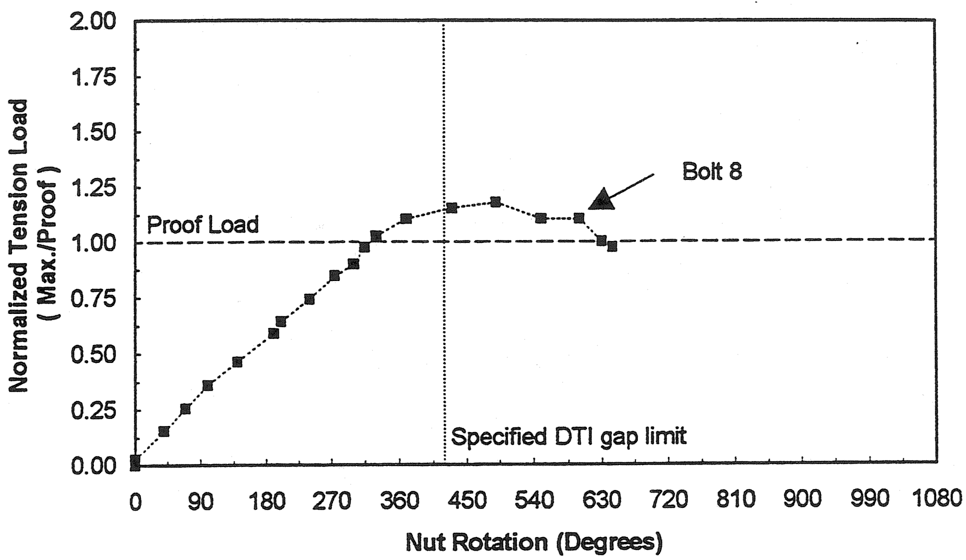
Graph 8 - Normalized Torqued Tension Vs. Nut Rotation Galvanized 7/8" Diameter, 3.5" Body Length A325 Bolts. Galvanized various "Old Style" DTIs, Installed using Method 1.



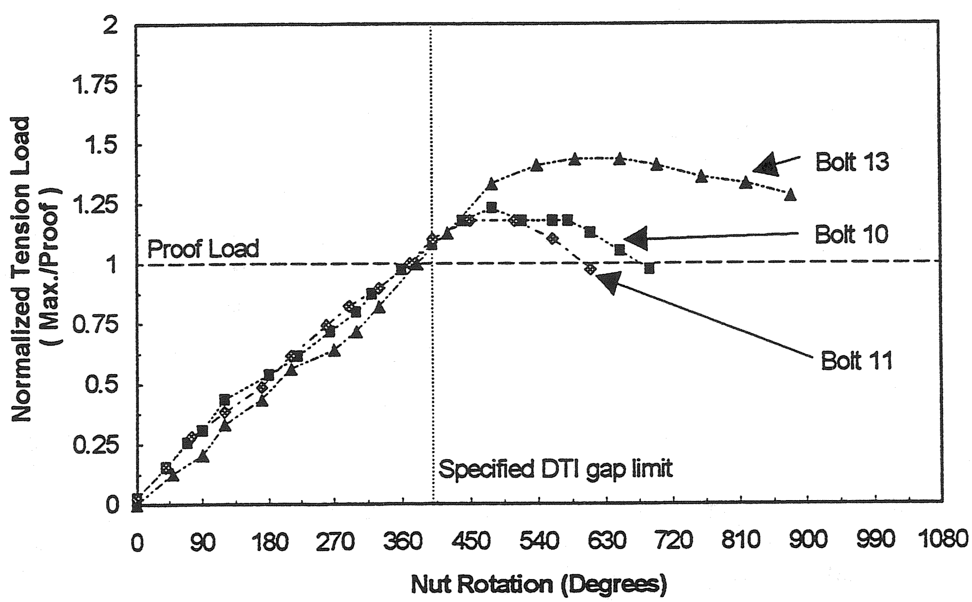
Graph 9 - Normalized Torqued Tension Vs. Nut Rotation Galvanized 7/8" Diameter, 3.5" Body Length A325 Bolts. Galvanized "New Style" DTIs, Installed using Method 1.



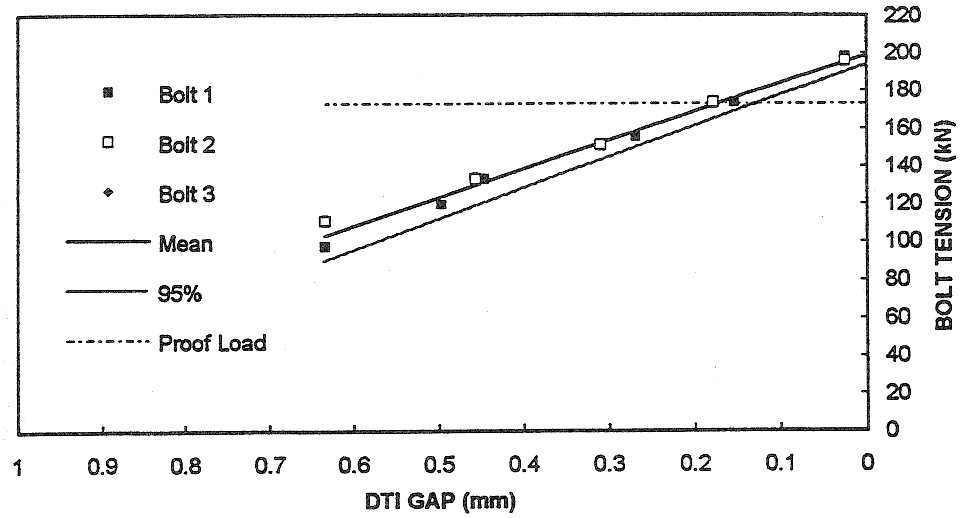
Graph 10 - Normalized Torqued Tension Vs. Nut Rotation Galvanized 7/8" Diameter, 3.5" Body Length A325 Bolts. Galvanized "Old Style - 325 Gap" Installed using Method 1.



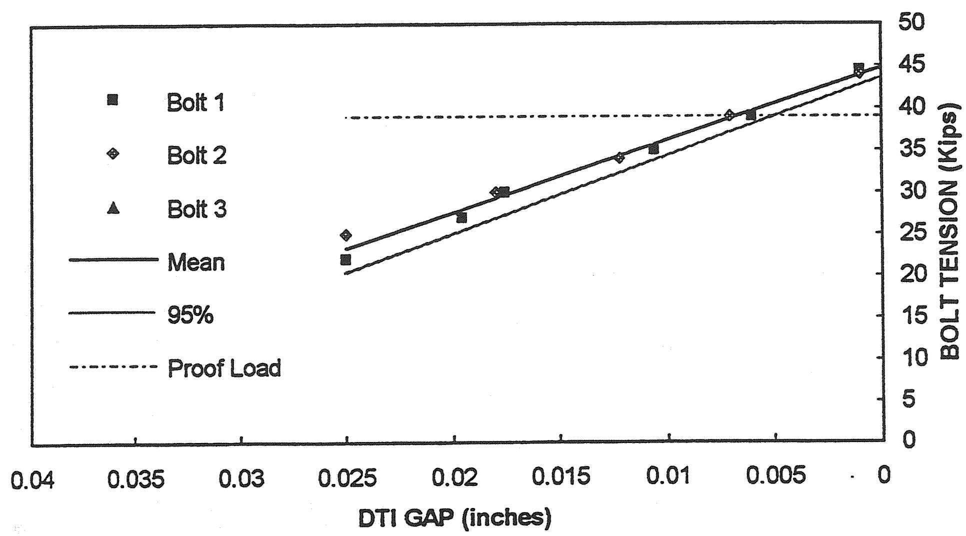
Graph 11 - Normalized Torqued Tension Vs. Nut Rotation Galvanized 7/8" Diameter, 3.5" Body Length A325 Bolts. Galvanized "Old Style - 325 Bump", Installed using Method 1.



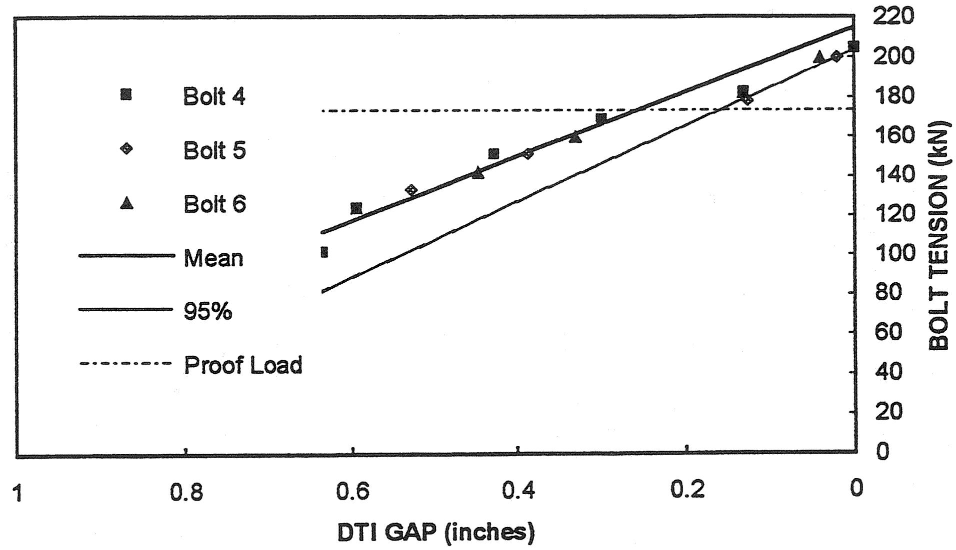
Graph 12 - Normalized Torqued Tension Vs. Nut Rotation Galvanized 7/8" Diameter, 3.5" Body Length A325 Bolts. Galvanized "Old Style - B Marking" DTIs, Installed using Method 1.



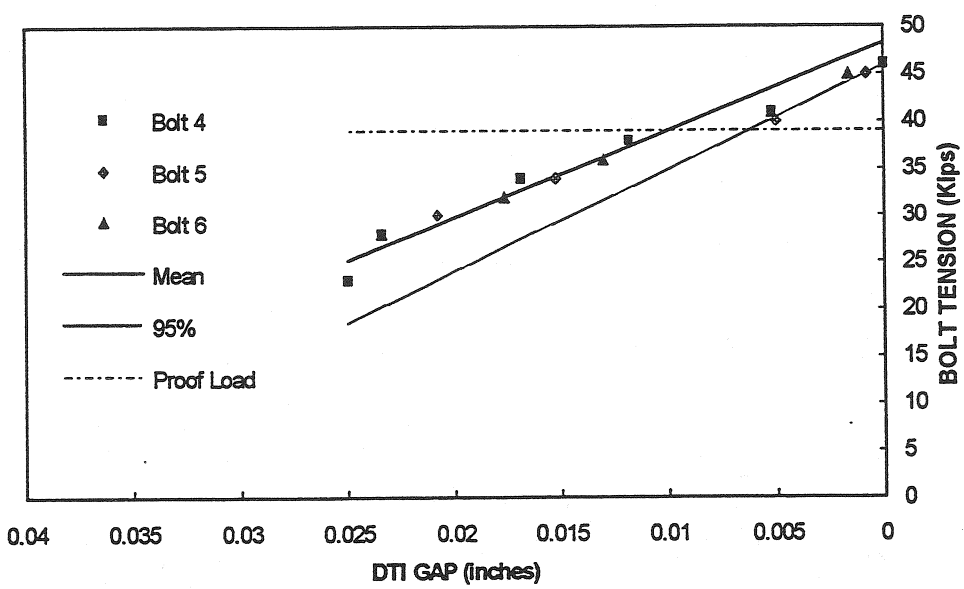
Graph 13a - Bolt Tension Vs. Average DTI Gap Weathering Steel 7/8" Diameter, 3.5" Body Length A325 Bolts. Epoxy coated DTIs, Installed using Method 1.



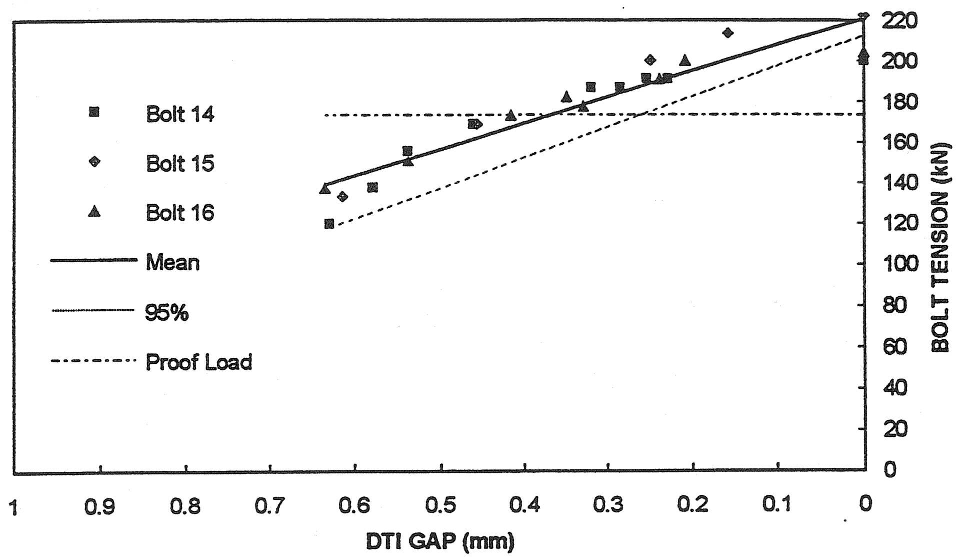
Graph 13b - Bolt tension Vs. Average DTI Gap Weathering Steel 7/8" Diameter, 3.5" Body Length A325 Bolts. Epoxy coated DTIs, Installed using Method 1.



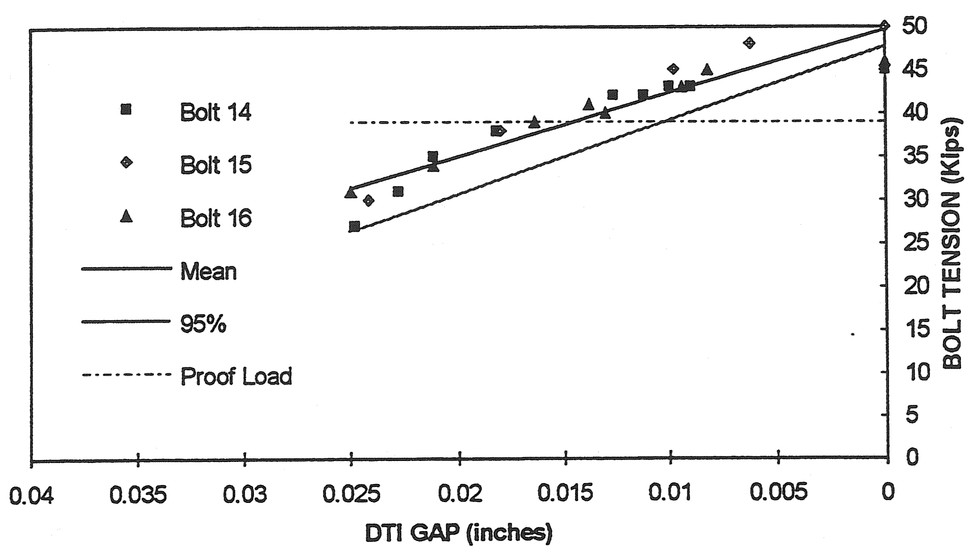
Graph 14a - Bolt Tension Vs. Average DTI Gap
Weathering Steel 7/8" Diameter, 5" Body Length A325 Bolts.
Epoxy coated DTIs, Installed using Method 1.



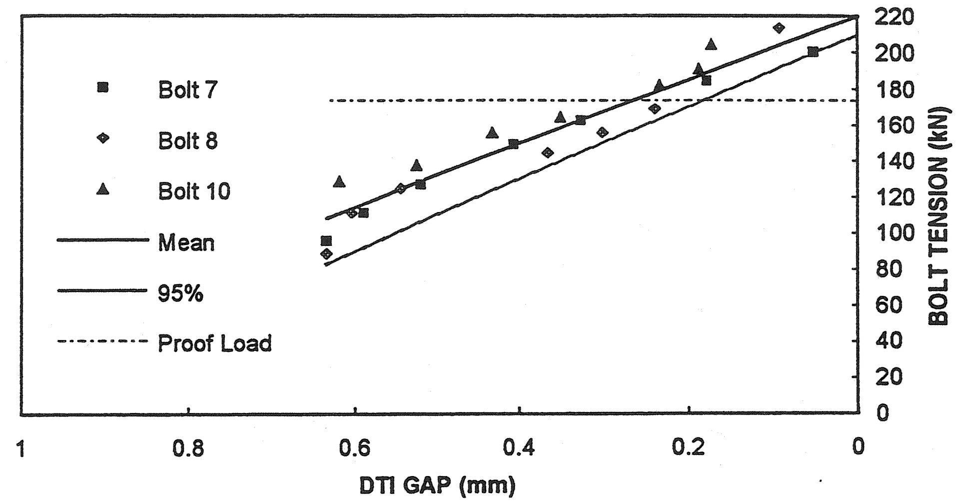
Graph 14b - Bolt Tension Vs. Average DTI Gap
Weathering Steel 7/8" Diameter, 5" Body Length A325 Bolts.
Epoxy coated DTIs, Installed using Method 1.



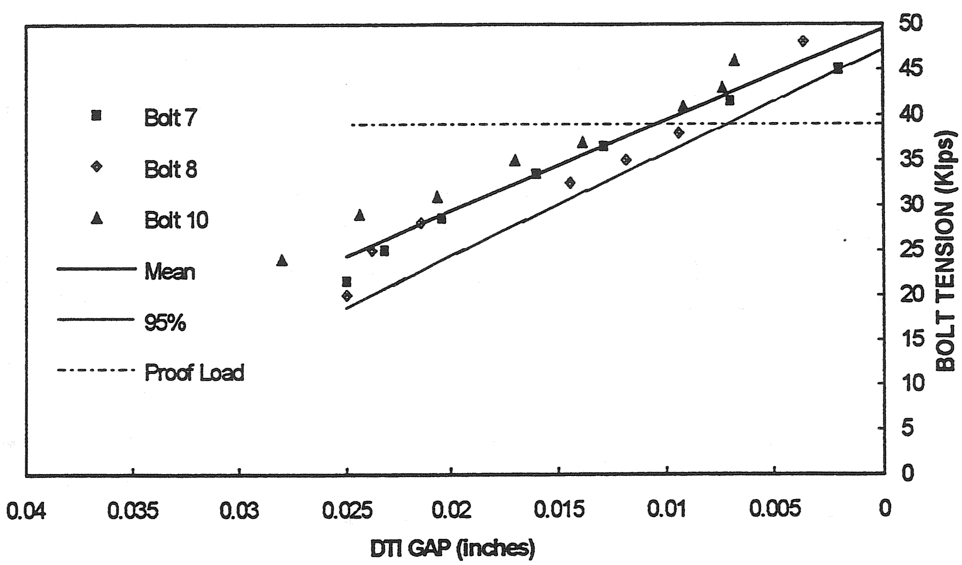
Graph 15a - Bolt Tension Vs. Average DTI Gap
Plain 7.8" Diameter, 3.5" Body Length A325 Bolts.
Plain DTIs, Installed using Method 1.



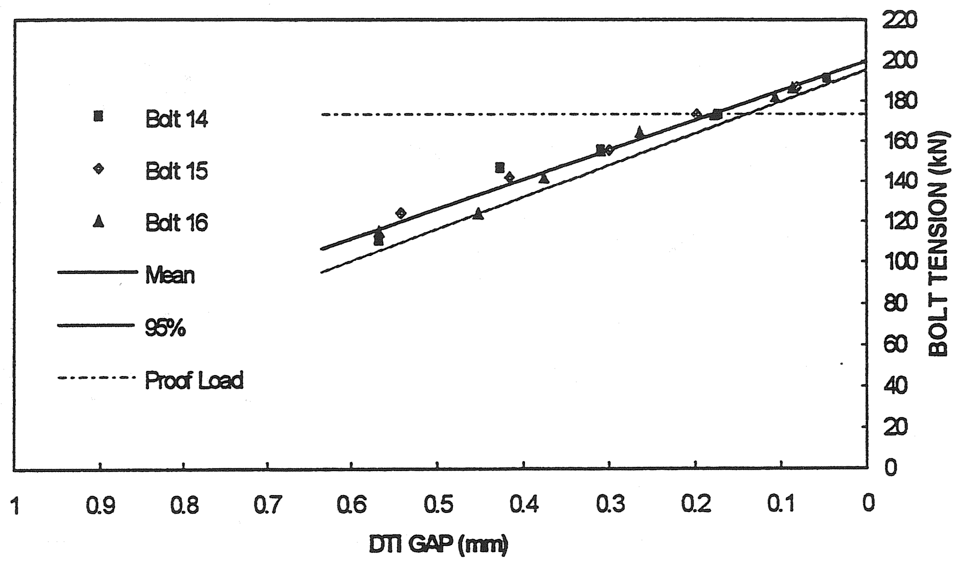
Graph 15b - Bolt Tension Vs. Average DTI Gap
Plain 7/8" Diameter, 3.5" Body Length A325 Bolts.
Plain DTIs, Installed using Method 1.



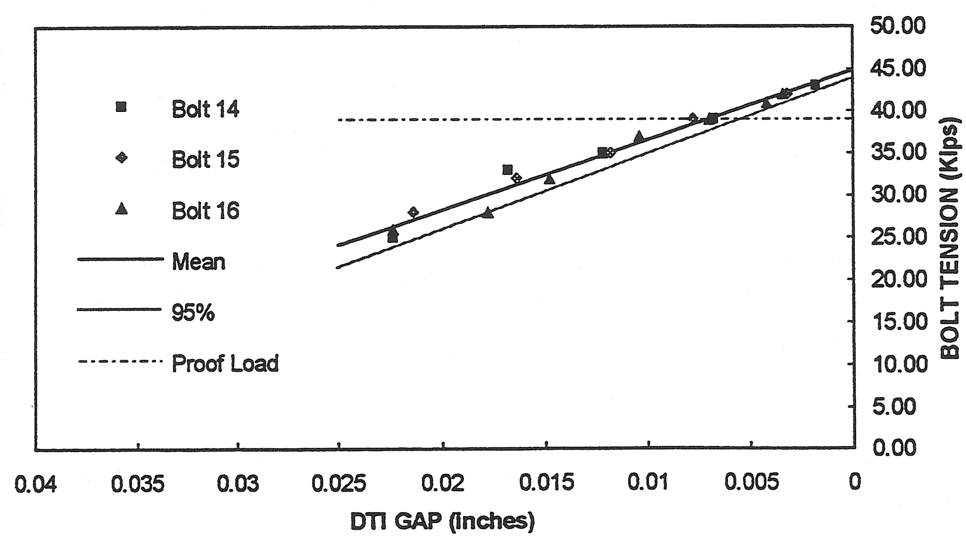
Graph 16a - Bolt Tension Vs. Average DTI Gap
Plain 7/8" Diameter, 5" Body Length A325 Bolts.
Plain DTIs, Installed using Method 2.



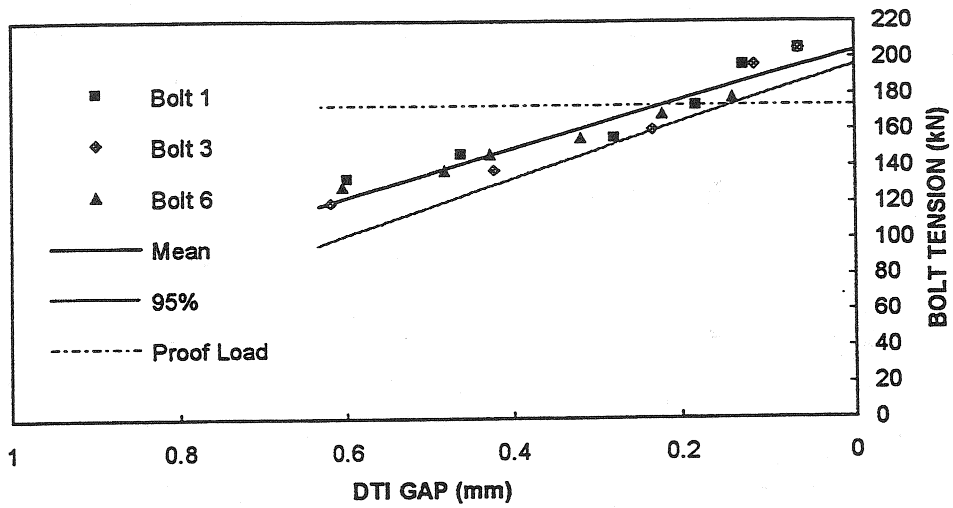
Graph 16b - Bolt Tension Vs. Average DTI Gap
Plain 7/8" Diameter, 5" Body length A325 Bolts.
Plain DTIs, Installed using Method 2.



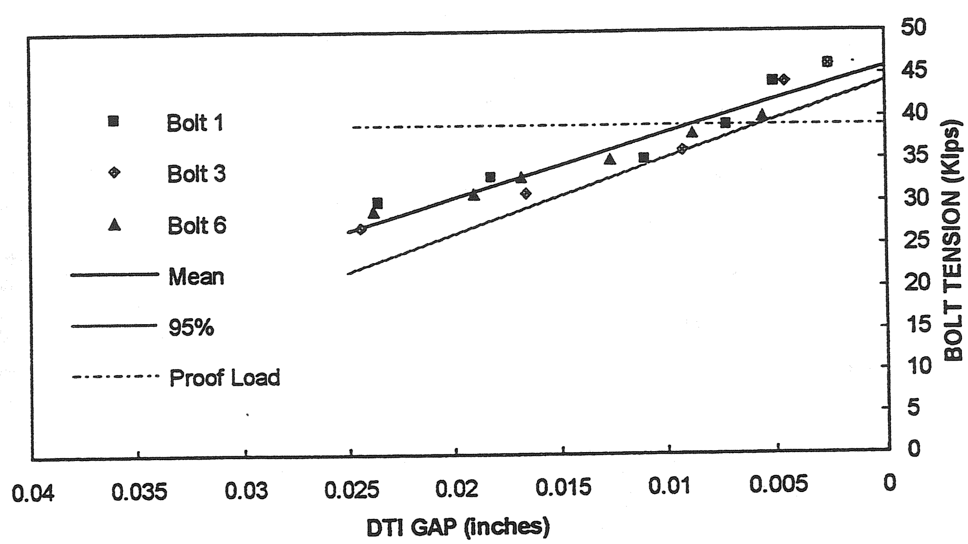
**Graph 17a - Bolt Tension Vs. Average DTI Gap
Plain 7/8 Diameter, 5" Body length A325 Bolts.
Plain DTIs, Installed using Method 1.**



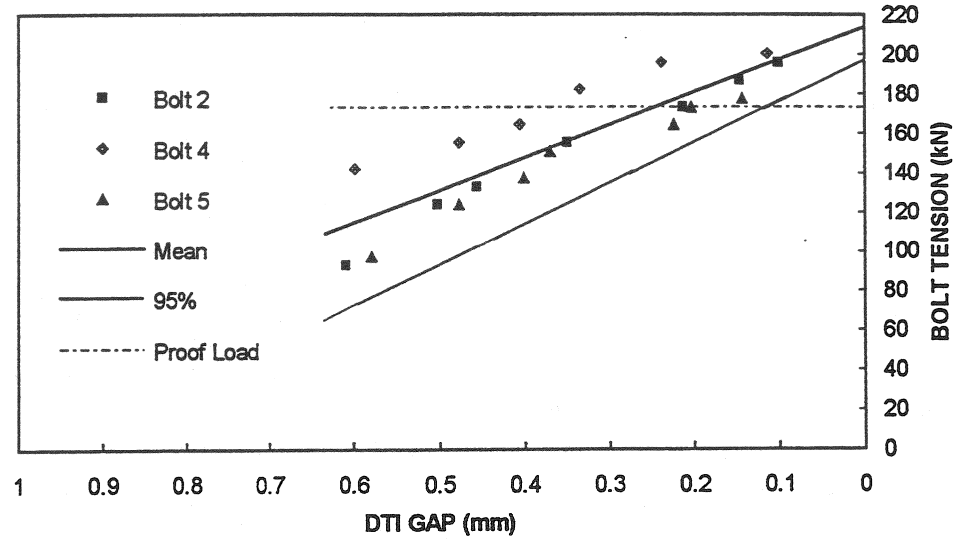
**Graph 17b - Bolt Tension Vs. Average DTI Gap
Plain 7/8" Diameter, 5" Body Length A325 Bolts.
Plain DTIs, Installed using Method 1.**



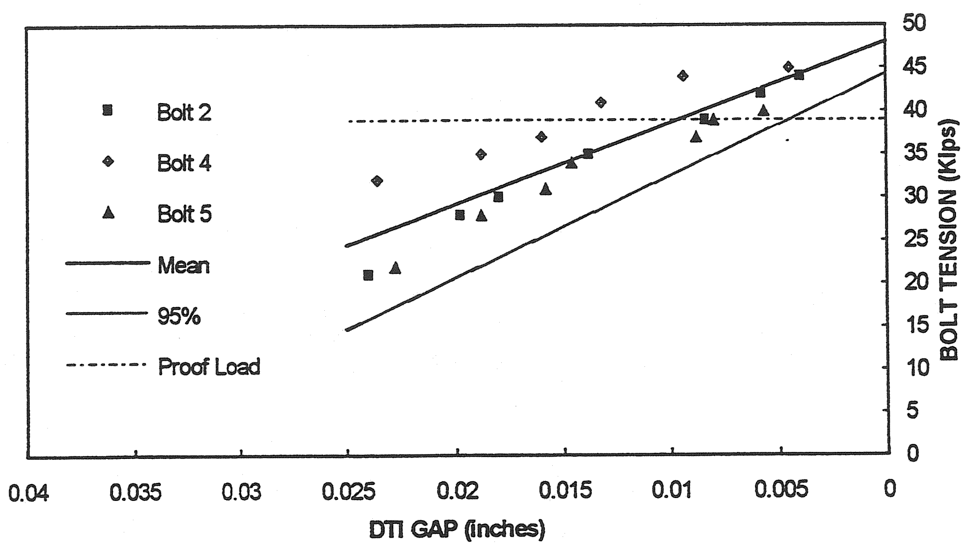
**Graph 18a - Bolt Tension Vs. Average DTI Gap
Galvanized 7/8" Diameter, 3.5" Body Length A325 Bolts.
Various Galvanized "Old Style" DTIs, Installed using Method 1.**



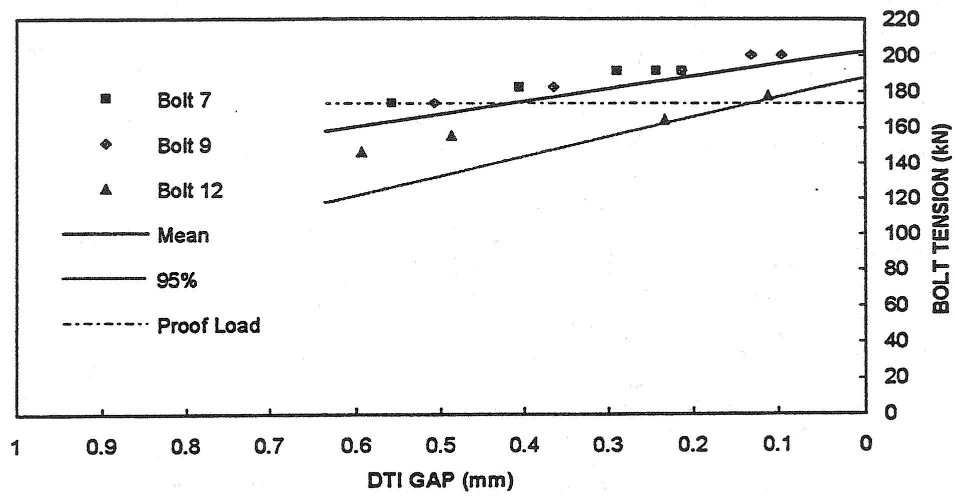
**Graph 18b - Bolt Tension Vs. Average DTI Gap
Galvanized 7/8" Diameter, 3.5" Body Length A325 Bolts.
Various Galvanized "Old Style" DTIs, Installed using Method 1.**



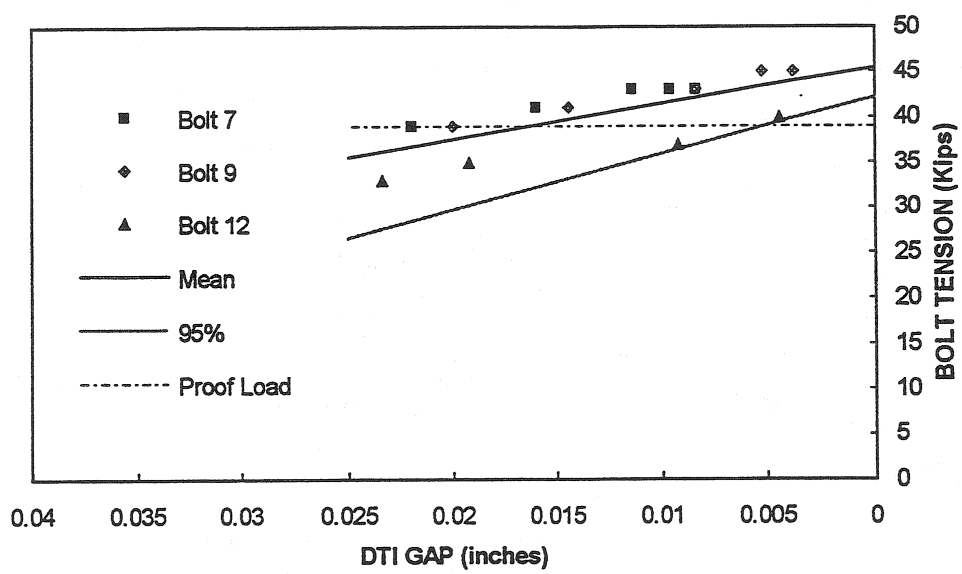
Graph 19a - Bolt Tension Vs. Average DTI Gap
Galvanized 7/8" Diameter, 3.5" Body Length A325 Bolts.
Galvanized "New Style" DTIs, Installed using Method 1.



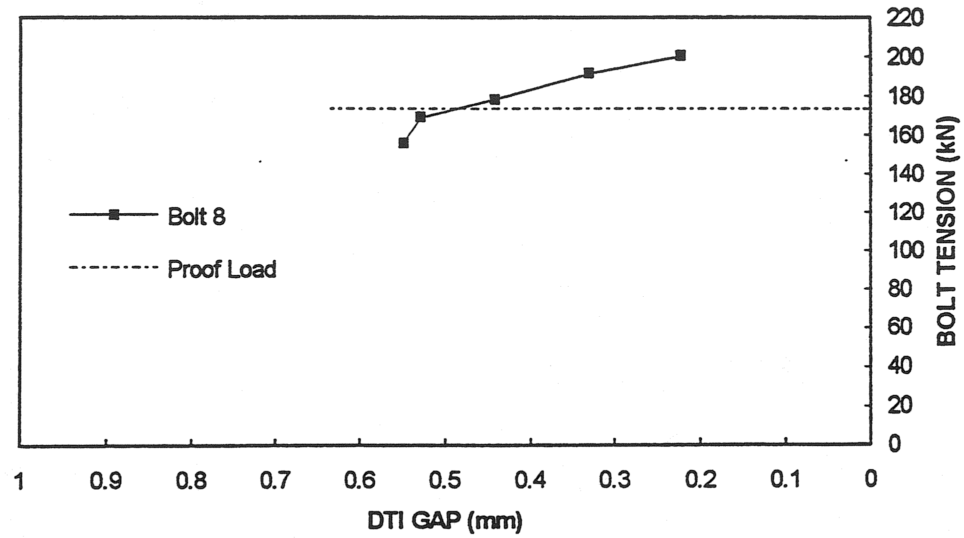
Graph 19b - Bolt Tension Vs. Average DTI Gap
Galvanized 7/8" Diameter, 3.5" Body length A325 Bolts.
Galvanized "New Style" DTIs, Installed using Method 1.



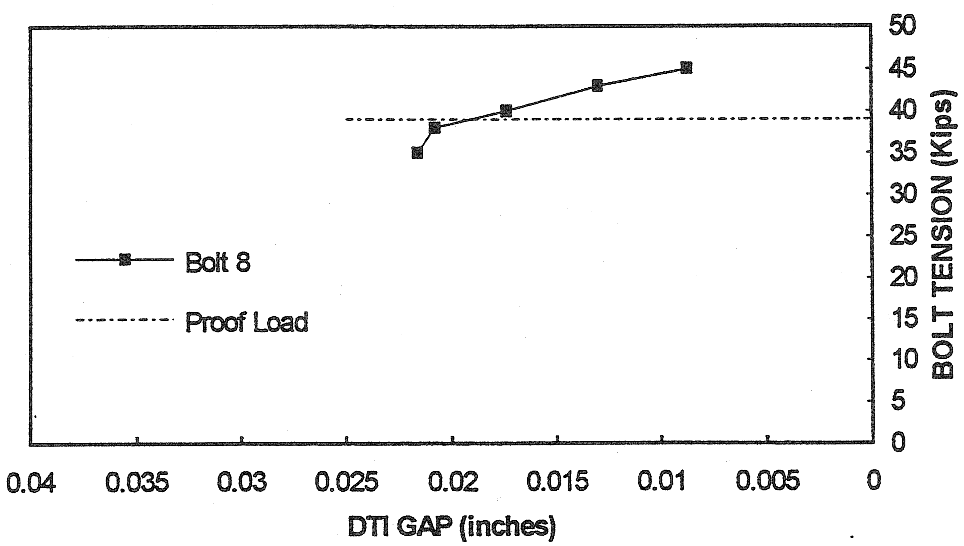
Graph 20a - Bolt Tension Vs. Average Nut Rotation
Galvanized 7/8" Diameter, 3.5" Body Length A325 Bolts.
Galvanized "Old Style - 325 Gap" DTIs, Installed using Method 1.



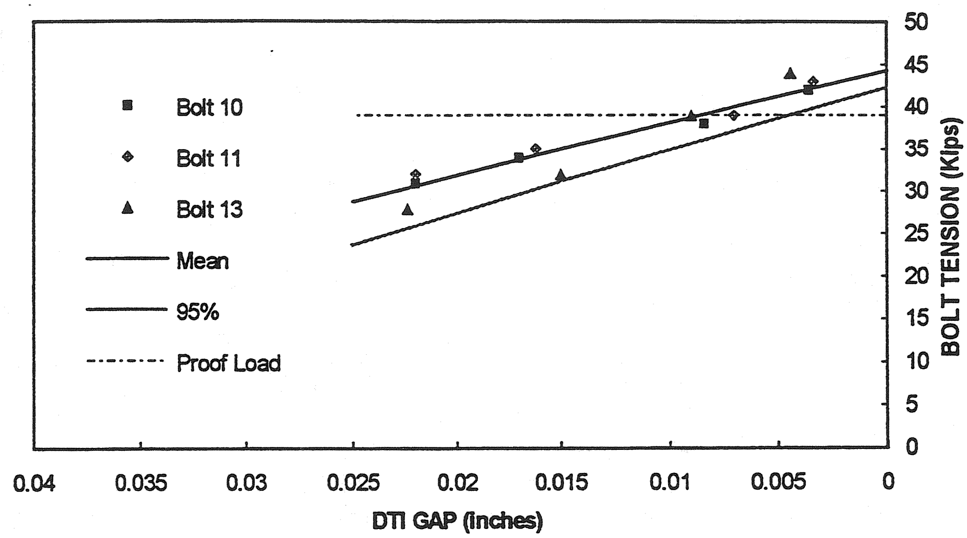
Graph 20b - Bolt Tension Vs. Average DTI Gap
Galvanized 7/8" Diameter, 3.5" Body Length A352 Bolts.
Galvanized "Old Style - 325 Gap" DTIs, Installed using Method 1.



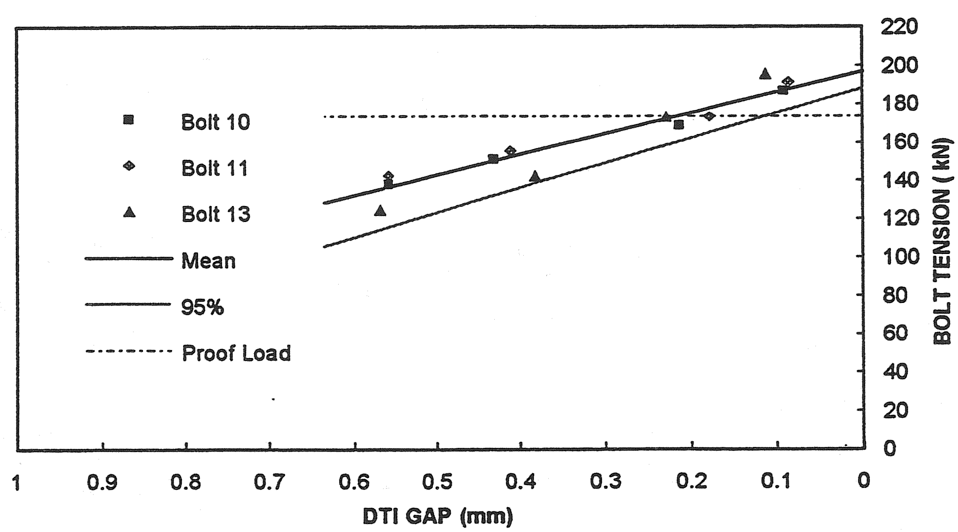
Graph 21a - Bolt Tension Vs. Average DTI Gap
Galvanized 7/8" Diameter, 3.5" Body Length A325 Bolts.
Galvanized "Old Style - 325 Bump" DTIs, Installed using Method 1.



Graph 21b - Bolt Tension Vs. Average DTI Gap
Galvanized 7/8" Diameter, 3.5" Body Length A325 bolts.
Galvanized "Old Style - 325 Bump" DTIs, Installed using Method 1.



Graph 22a - Bolt Tension Vs. Average DTI Gap
Galvanized 7/8" Diameter, 3.5" Body Length A325 Bolts.
Galvanized "Old Style - B Marking" DTIs, Installed using Method 1.



Graph 22b - Bolt Tension Vs. Average DTI Gap
Galvanized 7/8" Diameter, 3.5" Body Length A325 Bolts.
Galvanized "Old Style - B Marking" DTIs, Installed using Method 1.

Concentric Compressive Double Shear

Theoretically there are three sources that can introduce tensile loading to a bolt being tested in compressive shear. These factors are: 1) the prying action of the shear plates; 2) catenary action induced by the bending of the bolt; and 3) the preload induced during the installation of the bolt. All three of these factors have the potential either, singularly or in combination, to lessen the ultimate capacity of a bolt when compared to that of shear alone.

The prying action of the plates can be introduced at any level of loading. This prying action is introduced by the pulling away of the side plates of the test apparatus as shear forces are applied. In field connections the side plates are the connecting plates and are responsible for introducing the same tensile effects. This prying action introduces axial loading and deformation in the bolts. However, it has been found in most common connection applications that axial loading introduced by prying action is minor in comparison to the actual yield stress of the bolt[7]. To illustrate the small effect prying action has in shear capacity, studies have been done which show that tensile stresses equal to 20-30% of the bolt's tensile strength have insignificant effects on its shear strength[14].

Catenary action is the result of the bolt bending as shear forces are applied and is present in both concentric compressive and eccentric tensile shear applications. Catenary action can be identified as a bending or "cupping" of the bolt's longitudinal axis. This effect is most prevalent at tension states close to ultimate load. This "cupping" effect of the bolt is believed to increase axial tension as a bolt approaches ultimate load. However, the effect introduced by catenary action is believed to be even smaller in comparison to those introduced by prying action. Thus, the catenary action of concentric compressive and eccentric tensile shear loading has even less effect on the ultimate shear strength of a bolt than the prying action discussed in the preceding paragraph[15]

Test results for the concentric compressive double shear test series are summarized as graphs of Normalized Shear Load vs. Nut Rotation. Loads were normalized by taking the ratio of the experimentally recorded maximum shear capacity and the nominal theoretical shear strength given by Equation 2. The data gathered in the concentric compressive shear testing of the plain, galvanized and weathering steel bolts are illustrated in Graph 23 through Graph 26. In each of these four graphs the normalized load (max. recorded/unfactored design strength) is plotted against the degree of rotation in each bolt (the unfactored design strength is 86.5 kips using LRFD[10], see Equation 2). Graphs 23 through 25 illustrate normalized concentric compressive shear data for one of the three types of bolts being tested in this research; Galvanized, Plain and Weathering Steel bolts, respectively. Graph 26 illustrates all three bolt types and their normalized concentric compressive shear data on one plot.

Theoretical Nominal Shear Strength - No Threads in Shear Planes

$$R_n = \left(0.60F_u^b\right)mA_b \qquad \textbf{Equation - 2}$$

$R_n =$ Unfactored nominal shear strength of fastener.

$0.60 =$ Reduction factor.

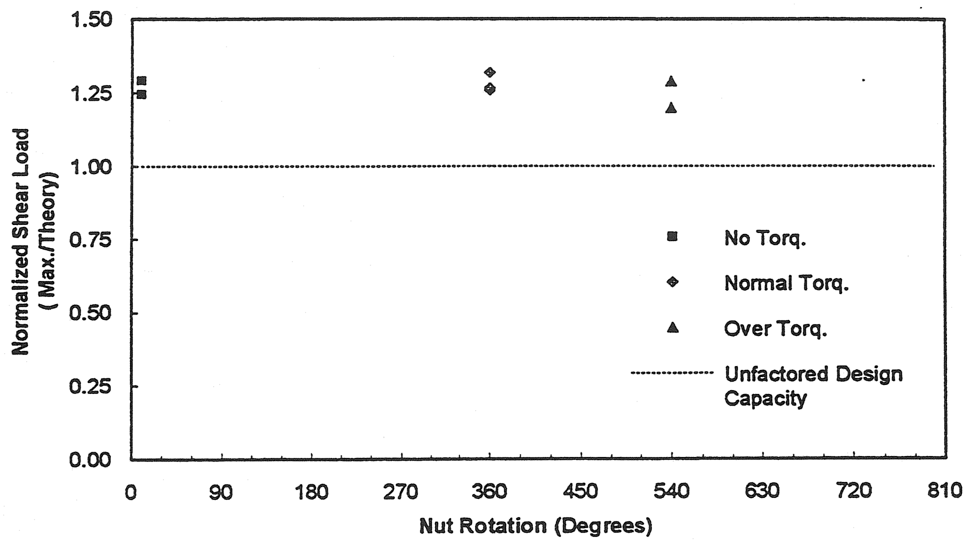
$F_u^b =$ Tensile strength of bolt material (120 ksi for A325 bolts; 150 ksi for A490 bolts)

$m =$ The number of shear planes participating.

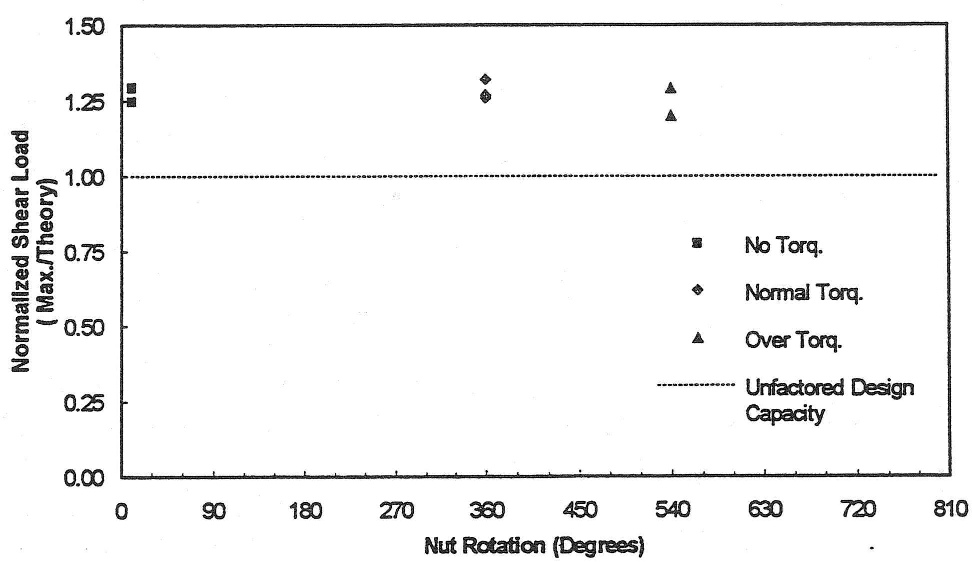
$A_b =$ Gross cross-sectional area across shank of bolt.

The normalized shear for all bolts tested exceeded the unfactored design capacity. Thus all bolts, irrespective of their degree of tightening, were found to provide the minimum required compressive shear capacity. All bolts provided acceptable shear and their shear capacity was found not to be significantly affected by bolt over-tightening. It should also be noted that in all bolts tested in double shear, catenary effects were evident (See Photograph 5). Upon inspection of the test apparatus after concluding each bolt failure, prying effects were also noted. These prying effect were visible in the form of ovaling, etching and raising of the lips around the bolt holes of the side and center plates of the compression shear testing apparatus. Since the shear capacity was not reduced, this confirms that catenary and prying actions have a negligible effect on shear capacity.

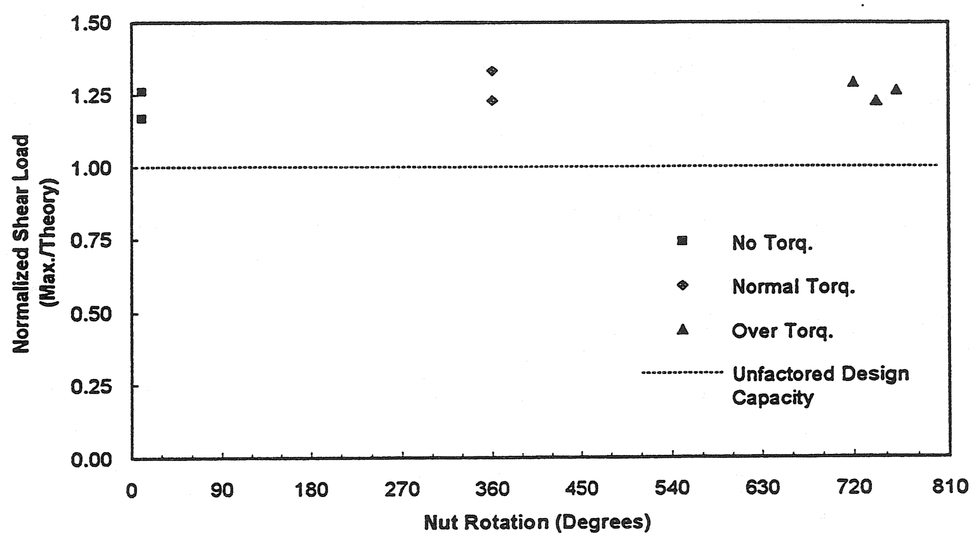
As the four graphs show, there appears to be no evidence that shear capacity is a function of the degree to which a high-strength bolt is tightened. Likewise, shear strength in double shear is not affected by catenary and/or prying actions. From these graphs it is clear that the paramount factor controlling shear capacity is the cross-sectional area available to the shear plane. Based on this evidence, it is apparent that if a bolt is tightened to any degree of rotation short of that which causes failure, then the bolt's shear capacity will not be affected and will be controlled solely by the material area available to the shear plane as long as the clamping force is not reduced excessively. Examples of high-strength, 7/8" diameter, 5 inch body length bolts, A325 bolts tested in double shear are pictured in Photograph 5.



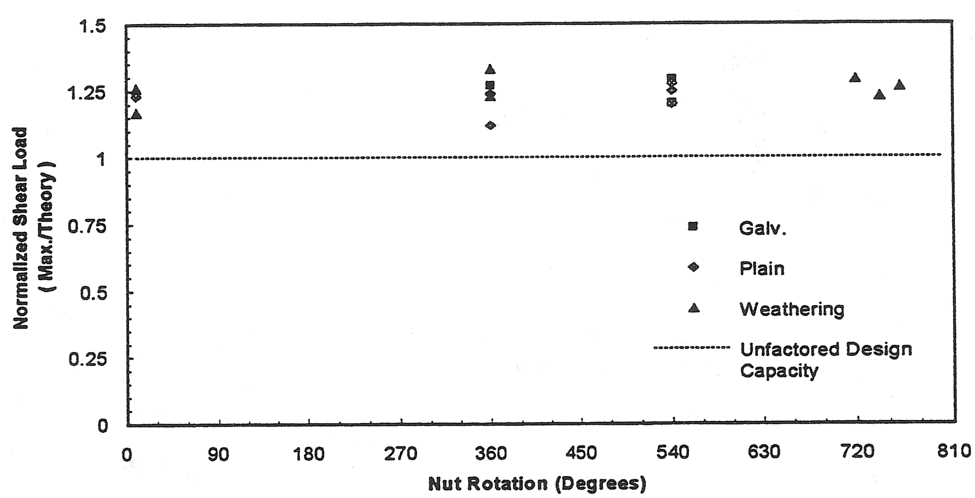
Graph 23 - Normalized Compressive Shear Load Vs. Nut Rotation. Galvanized 7/8" Diameter. 5" Body Length A325 Bolts.



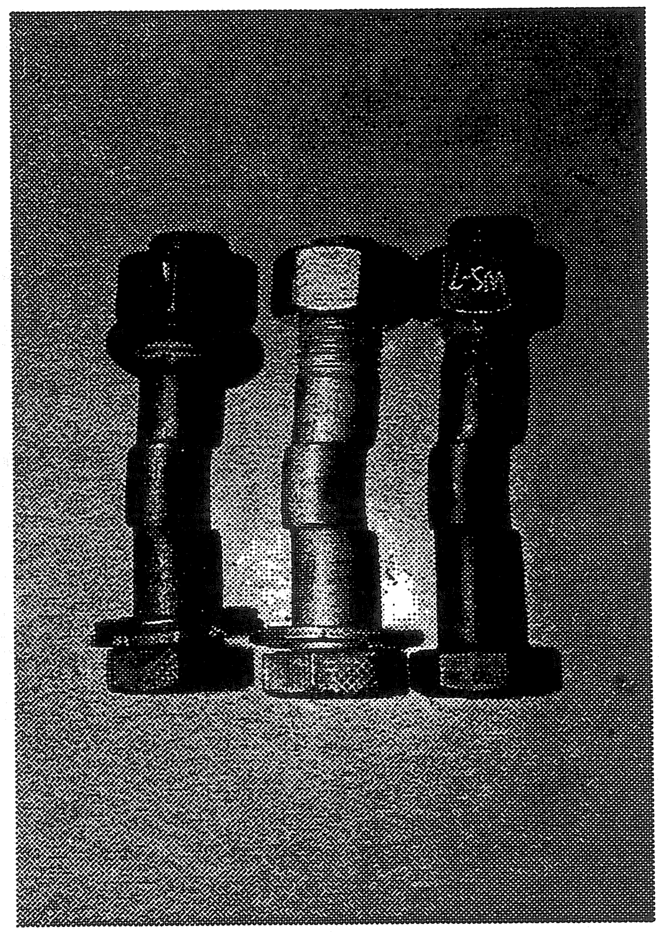
Graph 24 - Normalized Compressive Shear Load Vs. Nut Rotation. Plain 7/8" Diameter, 5" Body Length A325 Bolts.



Graph 25 - Normalized Compressive Shear Load Vs. Nut Rotation. Weathering Steel 7/8" Diameter, 5" Body Length A325 Bolts.



Graph 26 - Normalized Compressive Shear Load Vs. Nut Rotation. Galvanized, Plain and Weathering Steel 7/8" Diameter, 5" Body Length, A325 Bolts.



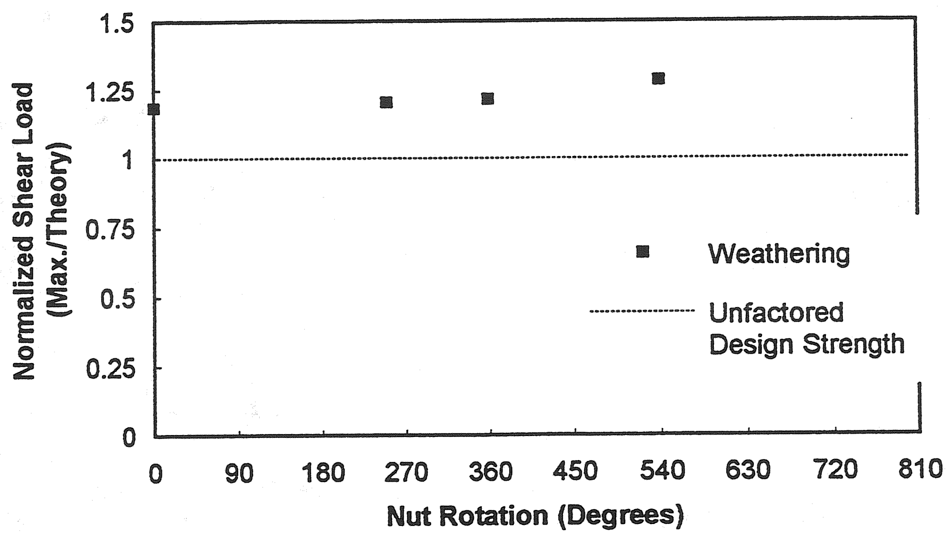
Photograph 5 - Example of Bolts Tested in Concentric Compressive Double Shear.

Eccentric Single Tensile Shear

The three factors of prying action, catenary action and preload loss, described in the previous section, can also affect the shear capacity of bolts tested in eccentric single tensile shear. It is true that the effects of prying action are more significant in eccentric shear loading conditions; however researchers have found this to be small in comparison to direct tension effects for normally tightened bolts[9]. Each of these three factors is believed to act in eccentric single tensile shear as they do in concentric compressive double shear.

With the addition of eccentricity to the testing apparatus, a fourth factor must now also be considered, namely, the combined tension and shear components introduced by the eccentricity and how they affect tensile shear performance. Tests done on A325 bolts and their combined loading conditions at the University of Illinois[7, 10] showed that as grip length increases so does ultimate load capacity in single eccentric shear. For both 3-1/2 and 5 inch body length bolts a grip length representative of common single-ply connections was used.

As in the compressive shear testing, the eccentric tensile shear result are presented in plots of Normalized Shear Load vs. Nut Rotation. In single shear, the capacity of a A325, 7/8 inch diameter is theorized to be 43.3 kips (Equation 2, with $m = 1$). In Graph 27, as with bolts tested in concentric shear tests, all bolts tested had a normalized eccentric single shear capacity above the normalization line (unity). Again, we see that the eccentric single shear capacity of bolts tested are not affected by the degree to which the bolt was tightened, by catenary action, prying action, loss of preload or combined loading conditions. The test apparatus, due to the eccentricity of the loading, showed even more signs of prying and catenary action than the concentric double shear tests. However, this additional prying and catenary action caused no discernible reduction in shear capacity. Again, any tightening short of that causing bolt failure was observed to have no effect on the bolt's eccentric single shear capacity as long as the clamping force was not reduced below proof load. The ultimate capacity of the bolts tested in eccentric single tension shear was found to be a function only of the area available to shear plane.



Graph 27 - Normalized Eccentric Tensile Shear Vs. Nut Rotation Weathering Steel 7/8" Diameter, 5" Body Length A325 Bolts.

SUMMARY

This research was performed at the request of the Idaho Transportation Department. The ITD was concerned about the systematic "over-tightening" of high-strength bolts used on one of its recent bridge projects. The key question that the ITD wished investigated was: " What effects can be experienced by a structure designed with high-strength bolted connections that have been systematically over-tightened"?

The results of the investigation into the effects of systematically over-tightening high-strength bolts used in bolted connections, accompanied by any relevant secondary findings and/or observation are as follows:

There was no evidence to support a loss of concentric compressive or eccentric tensile shear capacity when high-strength bolts are designated "over-tightened". In both cases where high-strength bolt have been "over-tightened" in concentric compressive and eccentric tensile shear, no loss of shear capacity was observed. In final analysis, all bolts tested in concentric compressive and eccentric tensile shear were found to exhibit ultimate shear capacities that were a function of the bolt's material area available to the shear plane or planes[18].

Many secondary observation were also generated during the course of this investigation:

- ☐ In both concentric compression and eccentric tension shear, bolts tested exhibited shearing capacities in excess of minimum requirements despite being over-tightened.

- ☐ Although both types of shear failure exhibited prying and catenary action, these factors were found to be negligible in the determination of a bolt's ultimate shear capacity.

- ☐ The combined effects of tension and shear introduced by eccentricity were also observed not to affect the ultimate shear capacity of a bolt tested in single tension shear.

- ☐ In this research only well lubricated bolts were evaluated. The test results are not applicable for "dry" installed high-strength bolts.

- ☐ For the A325 weathering steel bolts tested, a drop in shear capacity of between 8 and 13% was not observed in going from concentric compression to eccentric tension shear as cited by previous researchers[8].

- ☐ There exists a positive correlation between the turn-of-nut method and the DTI method for verifying proof loading.

- ☐ In the use of the DTI method for verification of proof loading, the inherent problems of the turn-of-nut method are eliminated (strain control and control over accuracy of nut rotation).

- Bolt lubrication significantly affected the ease with which bolts could be tightened, and can be very instrumental in the reduction of galling effects, as evident by DTI gap readings and through verification of nut rotation in the turn-of-nut method.

- Although several DTI protrusion configurations exist, all DTIs reliably indicate the proof load experienced by a high-strength bolt.

As load indicating devices, DTI must be installed properly. Both contractor and inspector should review proper installation techniques (i.e., J & M Turner Handbook) before each project to ensure that DTIs are being installed and inspected properly.

DTIs verify proof loading in high-strength bolts if installed by either Method 1 or Method 2. The DTIs designated as "New Style" are more closely correlated with respect to proof load reading, however all DTI protrusion configurations will always achieve proof loading.

The results of this research were found to be consistent with recent and historical studies reported in literature. Specific modifications to the current installation practices governing the usage of DTIs were not proposed.

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